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ASD TECHNICAL REPORT 61-696

RESEARCH AND DEVELOPMENT OF DESIGN CONCEPTS FOR SEALING APPLICATIONS IN AEROSPACE VEHICLE CABINS

Joseph S. Islinger

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AERONAUTICAL SYSTEMS DIVISION

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FOREWORD

The research work in this report was performed by Armour Research Foundation, Chicago 16, Illinois, for the Flight Dynamics Laboratory, Directorate of Aeromechanics, Deputy Commander/Technology, Aeronautical Systems Division, Wright-Patterson Air Force Base, under AF Contract No. AF 33(616)-7194. This research is part of a continuing effort to obtain criteria and techniques for providing absolute cabin sealing for flight vehicles, which is part of the Air Force Systems Command's Applied Research Program 750A, the Mechanics of Flight. The Project Nr. is 1368 "Design Technologies and Structural Configuration Concepts for Aerospace Vehicles" and the Task Nr. is 136805 "Sealed Cabin Technology". Kennerly H. Digges of the Flight Dynamics Laboratory was the Project Engineer. The research was conducted from 1 April 1960 to December 15, 1961.

Armour Research Foundation staff members who contributed to the research described in this report include L. C. Bennett, E. R. Cokeing, C. E. Donarski, J. S. Islinger (project engineer), E. H. Koeller, R. J. Larson, H. R. Nelson, S. E. Noreikis, S. Pinsky, R. C. Reichel and J. S. Shanly. (Data obtained in the course of the investigations are recorded in ARF Logbooks C9922, C10908 and C11392).

ABSTRACT

This report describes the development of near absolute sealing techniques for small openings, such as for electrical conductors, reciprocating and rotating shafts, and hatches in the walls of flight vehicle cabins. The need for absolute sealing stems from the requirement of a habitable environment in such vehicles for periods as long as one year under differential pressure and temperature extremes from -100 to +500°F. The considerations underlying selection of suitable seal materials for resistance to the space environment, comprising radiation, high vacuum, temperature and static and dynamic loading, are discussed. The mechanical design and material factors considered conducive to and studies leading to a definition of absolute sealing are also discussed. Special investigations concerned with effect of elastomer permeability upon seal behavior and with techniques for adequately sealing electrical wires and cables were undertaken and are described. The developed seal concepts for each of the four sealing applications considered are described in detail and results of the evaluation tests performed under simulated environmental conditions in the ARF high vacuum environmental facility are presented. Recommendations are made regarding the use of the information generated on this program in the design and development of actual sealing concepts for space vehicle cabin applications.

PUBLICATION REVIEW

The publication of this report does not constitute approval by the Air Force of the findings or conclusions contained herein. It is published only for the exchange and stimulation of ideas.

FOR THE COMMANDER:

William C. Nielsen
WILLIAM C. NIELSEN
Colonel, USAF
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I. INTRODUCTION*

Future Air Force flight vehicles must operate in near vacuum environments. Such operations will require the reliable maintenance of a safe cabin atmosphere for the protection of occupants. Reliable methods for hermetic sealing of cabin structures are available, but the sealing of small openings such as holes for cables and shafts and for doors or hatches needs further attention. Accordingly, this program was undertaken and has as its objective the establishment of sealing methods for small leakage areas. Theoretical and experimental investigations were made of design concepts and materials to determine capabilities of specific designs and materials. The investigations were aimed at developing sealing methods applicable over the temperature range of -100 through +500°F to provide a habitable cabin environment in a space vehicle for periods as long as one year.

Factors affecting the mechanical design of seals under investigation include internal pressure, external high vacuum, thermal expansion and contraction of the cabin structure, vehicle acceleration, shock and vibration, and dynamic and geometric properties of reciprocating and rotating shafts. The conditions underlying consideration of suitable seal materials for resistance to the space environment include radiation, hard vacuum, meteorite particles and temperature. The mechanical design and material factors considered conducive to positive sealing were also studied.

Generally the investigations on this program were concerned with the following: (1) The space environment considerations, i.e., the environmental conditions to which the space vehicle will be exposed that govern development of the seal design concepts, (2) the material considerations underlying selection of the suitable elastomer materials, (3) the factors involved in positive sealing, wherein it is shown that the only practical approach is one in which leakage is permitted (as opposed to hermetic sealing), (4) the development of seal mechanical design concepts, (5) fabrication of the seals and (6) evaluation of the seal design concepts under simulated space environment conditions. The seal applications considered and for which seal concepts were developed include (1) an electrical conductor seal (including concepts for shielded and unshielded cables), (2) a reciprocating shaft seal, (3) a rotating shaft seal, and (4) an outward opening escape hatch seal.

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II. SPACE ENVIRONMENT CONSIDERATIONS

The temperature range for which seals were developed on this program was divided into two phases. The Phase I temperature range extended from -65 to +250°F and the Phase II temperature range extended from -100 to +500°F. The Phase I temperature range was selected in order to provide an interim sealing material and design concepts for the more moderate temperature range. The aim for this temperature range was to provide as near a positive sealing condition as may be physically possible. For the broader temperature range of Phase II the aim was for a high degree of sealing with leakage past the seals to be minimized.

The normal internal cabin pressure to be sealed against was specified as 14.7 psia or atmospheric pressure. The normal external pressure was specified as 0 psia or a hard vacuum to 1.5 psia or a moderate vacuum. The seals were designed to withstand a temporary differential pressure of 30 psi. The seals and sealing methods were expected to be capable of withstanding all other environmental conditions such as radiation, etc. both internal and external to the earth's atmosphere. The sealing methods were to perform reliably for the period of at least one year. Finally, the sealing methods were to be effective indefinitely when subjected to accelerations over the range of 0 to 10 g's and to other shock and vibration inputs. Of course, since the sealing methods were to be developed for air and space craft, the weight of each seal concept was required to be held to a minimum. However, no attempt was made to optimize the designs from the standpoint of minimum weight.

III. MATERIAL CONSIDERATIONS

The important properties underlying selection of suitable materials for the seals included resistance to thermal, vacuum, and radiation conditions expected to be encountered, low air permeability, low friction or high abrasion characteristics, and other properties usually considered desirable in seals, including low compression set and resistance to ozone, aging and fuels. A comparison was made of several elastomer materials as candidates for Phase I seal materials. This comparison is shown in Table 1. It should be noted that the temperature limits presented in Table 1 are within safe limits of conventionally compounded stocks containing no plasticizers. The low temperature limit of some elastomers may be extended by the use of suitable additives. However the exposure of such materials to a vacuum environment is expected to degrade the materials through loss of the additives. Table 1 includes only a qualitative comparison of vacuum volatility or outgassing characteristics under the heading vacuum stability because of the very limited amount of information procured to date. Results of some vacuum outgassing tests reported for organic coatings (Ref. 1) and results of determinations of vacuum characteristics for certain elastomers (Ref. 2) have been the sources of information for vacuum stability characteristics in Table 1.

Table 1 reveals that most of the materials are suitable at the high temperature limit of 250°F for Phase I, but only the natural rubber approaches the low temperature service limit of -65°F. The air permeabilities shown in Table 1 were obtained from a study of air permeability of various elastomers as candidates for high temperatures summarized in reference 3. The results show that at both room temperature and a temperature of 176°F butyl rubber has the lowest air permeability. Next at room temperature come neoprene and nitrile rubber, then SBR or styrene-butadiene and finally Hypalon. No information was available on natural and on polyurethane rubber. At the higher temperature butyl is followed by Hypalon, nitrile and neoprene in that order with polyurethane and SBR tagging along last. Again no information was found on natural.

The several sources of information on vacuum stability (c.f. Ref. 4) indicate that SBR has excellent resistance. Next comes natural, followed by butyl and neoprene, and, last, polyurethane. No information was available for nitrile and Hypalon. For resistance to abrasion, the polyurethanes are best followed closely by Hypalon. Next come neoprene, nitrile, butyl and natural rubber, with SBR in last position. The polyurethanes and neoprene have a relatively low compression set, while all the others with the exception of butyl have a medium compression set; butyl on the other hand has a medium to high compression set. Hypalon has a low coefficient of friction, while all the others with the exception of natural have an intermediate coefficient and natural has a high coefficient. Hypalon has excellent resistance to aging and to ozone followed by the polyurethanes, neoprene, butyl and nitrile; the aging and ozone resistance of natural and SBR is only fair to good.

The following can be said in regard to radiation resistance of the elastomers (based on information from Refs. 5 and 6): natural rubber resists the damage of high energy radiation better than the synthetics. Natural rubber is followed by Hypalon, neoprene, SBR and nitrile rubber. Butyl has a poor resistance to radiation. No information was found on polyurethane rubber.

The comparison of elastomers considered candidates for the Phase II sealing applications are presented in Table 2. All three materials have capability at the high temperature of +500°F but only the silicones show capability at the low -100°F end. The nitrile-silicone class of elastomers could have been included in this table, but were purposely omitted because of the unsatisfactory experiences reported by both ASD and by North American Aviation. Apparently there are problems with resistance to high temperature and to fuels which make them unattractive for sealing applications. The Vitons have excellent air permeability characteristics; whereas the silicones, in general, have very poor air permeability characteristics. No information was available on the fluorosilicones in regard to air permeability.

The silicones are excellent from the standpoint of vacuum stability and the Vitons are good; no information was available on the fluorosilicones. For resistance to abrasion, Vitons are good and the silicones and the fluorosilicones are poor. The silicones and Vitons have a low compression set. Both Vitons and the silicones have a low coefficient of friction; both the Vitons and the silicones and even the fluorosilicones have excellent resistance to aging and to ozone. The fluorosilicones and Vitons have excellent resistance to fuels whereas the silicones have poor resistance to fuels. The silicones and Vitons have only a fair resistance to radiation. Again no information was available on fluorosilicones.

On the basis of the above comparisons, among the Phase I candidate elastomers, Hypalon appeared to be the most outstanding material. Hypalon was chosen as one of the materials for a Phase I hatch seal. Other considerations to be discussed later in this report prompted the selection of a nitrile rubber (Buna-N) for some O-rings in a reciprocating hatch seal application also for Phase I. A Teflon material was chosen for some lip type seals in a rotating shaft seal application.

For the Phase II materials, silicone rubbers are the most outstanding class of materials, in spite of their poor air permeability and abrasion characteristics. Therefore silicone rubber was selected for all seal concepts for the Phase II range of applicability.

Table 1

COMPARISON OF PHASE I CANDIDATE ELASTOMERS FOR SEAL APPLICATION

Elastomer	High Temp. Service Limit (°F)	Low Temp. Service Limit (°F)	Abrasion Resistance	Compression Set	Air Permeability 10^{-7} cc/sec/cm/cm^2 At 75°F	At 176°F	Vacuum Stability
Polyurethane	250	- 40	Best	Low	-	2.3	Poor
Hypalon	275	- 40	Excellent	Medium	0.72	0.73	-
Neoprene	250	- 30	Very Good	Low	0.10	1.0-1.7	Fair
Nitrile	250	- 20	Very Good	Medium	0.13	0.8	-
Butyl	250	- 20	Very Good	Medium-High	0.02	0.32	Fair
Natural	200	- 60	Very Good	Medium	-	-	Good
SBR	220	- 40	Good	Medium	0.23	2.9	Excellent

Table 2

COMPARISON OF PHASE II CANDIDATE ELASTOMERS FOR SEAL APPLICATION

Elastomer	High Temp. Service Limit (°F)	Low Temp. Service Limit (°F)	Abrasion Resistance	Compression Set	Air Permeability 10^{-7} cc/sec/cm/cm^2 At 75°F	At 176°F	Vacuum Stability
Viton	500	- 40	Good	Low	-	0.88	Good
Silicone	550	-100	Poor	Low	12-33	35-44	Excellent
Fluorosilicone	450	- 65		Low	-	-	-

IV. FACTORS INVOLVED IN POSITIVE SEALING

The factors involved in positive sealing include: (1) the mechanical factors, such as seal geometry, clearances, static and dynamic loads, the nature of the sealing application itself, and the internal and external pressures that the seals are to withstand. (2) The material factors include the usual physical properties of the seal materials, the gas permeability characteristics, the vacuum volatility, and the temperature and radiation resistance characteristics. (3) Another factor involved in positive sealing is the sensitivity of the leak detection method utilized to detect and measure leakage past the seal.

A. Mechanical Factors

For hatch and sealing applications, doors and hatches should open inward, in view of the obvious advantage of utilizing the outward acting pressure differential afforded by an external near vacuum environment and an internal cabin pressure to assist in effecting the seal action. Quick opening escape doors, in contrast to intermittently used access doors, probably will require outward opening for reliable exit in the event of an emergency. Seals for such doors will not have the benefit of the pressure differential in aiding sealing action. This was the application considered in the development of a hatch seal concept on this program. Positive closing action combined with proper door and frame design probably will assure constant seal depression and seal effectiveness. However such seals can probably not achieve as high a degree of positive sealing as inward opening doors or hatches.

Many sealing mechanisms and theories exist in the literature for rotating and reciprocating shafts in which the factors such as shaft friction and lubrication, seal wear and abrasion, and leakage past the seal are treated. Seals for rotating shafts of interest on this program are applicable to shafts from 1/4 in. to 1 in. in diameter and with speeds up to 500 rpm. For such conditions and for pressure differentials of the low magnitude involved here, lip seals are generally adequate. Seals for reciprocating shafts up to 1 in. in diameter were considered with stroke reciprocation varying between 3 in. to 36 in. with frequencies of the order of 1 stroke per minute. For the large strokes involved, a considerable alignment problem may exist for the reciprocating shaft. Slight misalignments during any portion of the stroke may cause excessive leakage. Transverse accelerations imposed upon moving shafts and seals have necessitated special handling in the design concept stage. Unless the shaft is otherwise supported by means of a bearing at the point where the shaft passes through the cabin wall, transverse accelerations may cause large displacements in the shaft. The seal may be called upon to dampen these displacements. In so doing the seal may distort sufficiently to cause momentary leakage. This appears to be preferable however to utilizing a mechanical stop to limit transverse shaft displacement and thereby risk damaging the moving shaft. A series of O-ring seals is usually adequate for reciprocating shafts of this sort.

Insulated electrical wires and cables generally pose an unusual problem. Air may leak between the wires and the sheathing or insulation along the length of the wires. Normally when wires or cables pass through the cabin wall a connector is provided. Such connectors may be adequate from a sealing standpoint; however the electrical problems introduced by such connectors could hamper the effectiveness of the wires

as electrical conductors, and therefore on this program connectors were passed over in favor of alternative sealing methods. The sealing of electrical wires and cables therefore require devising a technique for blocking the passage of air along the wires.

B. Material Factors

Among the material factors involved in positive sealing the most important characteristics are the thermal, radiation, and vacuum stability of the materials and their air permeability. The properties of various candidate elastomers from the standpoint of these characteristics are reviewed in Part III of this report. The last factor mentioned, air permeability, is a very complex phenomenon. Involved in the permeability of a material to a gas is dissociation of the gas, solubility of the gas, and diffusion of the gas through the material. No attempt will be made here to discuss this phenomenon in detail. The effect of air permeability on seal materials can be calculated in terms of air leakage through a hypothetical seal. In Table 3,

Table 3

AIR LEAKAGE THROUGH PERMEABILITY AT 75°F
(For Hypothetical Hatch Seal, 1/4 x 1 x 18 In. Dia)

Elastomer	Permeability (10^{-7} cc/sec/cm/cm^2)	Air Leakage Per Year (cc)	Air Leakage Per Year (lb)
Butyl	0.02	15	4.0×10^{-5}
Silicone	22	16,100	0.043

the results of computation of air leakage by diffusion of air through a hypothetical gasket type hatch seal with dimensions of 1/4-in. thickness by 1-in. width in cross section and 18 in. in diameter are presented. Two elastomer materials with extremes in air permeability were chosen. Butyl rubber is known for its extremely low permeability, and, therefore, it is used in tires. Silicone rubber, on the other hand, has perhaps the highest known permeability of the elastomer materials. As seen in Table 3, at room temperature the permeability of butyl rubber is 0.02×10^{-7} cc/sec/cm/cm^2, while that of silicone rubber is 22×10^{-7} or roughly 1000 times as great. Both values are reported in reference 3 for thin membranes of 0.025 in. thickness under a pressure differential of 1 atmosphere. These permeabilities would result in air losses through the materials of 15 cc in one year for the butyl rubber and 16,100 cc in one year for the silicone rubber. These leakages are equivalent to 4.0×10^{-5} lb of standard air for the butyl rubber and 0.043 lb for the silicone rubber in a year's time. In Table 4 calculations of leakage via permeability at a temperature of 350°F are shown. For butyl rubber, the permeability increases roughly by 300 times room temperature permeability to 6.1×10^{-7}, whereas for silicone rubber the permeability only increases 5 times to 112×10^{-7}. The

air leakages are 4600 and 82,000 cc per year, respectively, or 0.012 and 0.22 lb per year, respectively. Obviously even though silicone rubber materials have a far greater permeability to air than butyl, the resulting air loss in terms of lb of air per year is negligibly small due to diffusion of the air through the elastomer. It may be further noted that air loss through permeability can be decreased by compression of the seals, and, obviously, by decreasing the cross sectional area of the seals exposed to the pressure differential.

Table 4

AIR LEAKAGE THROUGH PERMEABILITY AT 350°F
(For Hypothetical Hatch Seal, 1/4 x 1 x 18 In. Dia)

Elastomer	Permeability (10^{-7} cc/sec/cm/cm^2	Air Leakage Per Year (cc)	(lb)
Butyl	6.1	4600	0.012
Silicone	112	82,000	0.22

C. Measurement Sensitivity

For leak determination and seal evaluation in the laboratory, a factor involved in determining positive sealing is the sensitivity of the detection method or leakage measuring device. Therefore a discussion of leakage measuring techniques and the sensitivities thereof is warranted. In Table 5 several leakage measuring techniques and devices are listed together with their sensitivities. They range from the ordinary gas meter with a sensitivity of 1.0 cu ft/hr through the mass spectrometer with a sensitivity of 1.3×10^{-11} cu ft/hr. The figure quoted for the water bubbling technique in Table 5, of 3.5×10^{-5} cu ft/hr, is based upon a simple laboratory determination. Leakage was determined by bubbling leaking air from an insulated wire with leakage controlled by a pinch clamp into a container of water. It was estimated that approximately four bubbles per minute were escaping from the wire. If these bubbles were about 2 mm in diameter, this would represent the leakage rate of approximately 1 cc/hr or 3.5×10^{-5} cu ft/hr. Among the other techniques the pressure drop method has the sensitivity of 10^{-3} cu ft/hr, microburettes about 3.5×10^{-7} cu ft/hr, halogen type leakage detectors about 1.3×10^{-7} cu ft/hr, the vacuum ionization gage about 2.3×10^{-8} cu ft/hr and, of course, the mass spectrometer of 1.3×10^{-11} cu ft/hr. Thus, determination of the degree of positive sealing of any particular sealing application is dependent upon the leakage measuring technique or device employed.

In order to establish some allowable leakage rates for application to space vehicles, the practical approach of allowing some leakage was taken rather than that of trying to meet the unrealistic (in this case) leakage rates specified for hermetic seals, such as given in Reference 6 or similar specifications for hermetic sealing applications.

Table 5

SENSITIVITY OF LEAKAGE MEASURING TECHNIQUES

Technique	Leakage Rate	Sensitivity (cu ft/hr)
Gas Meter	1.0 ft^3/hr	1.0
Pressure Drop	1.0×10^{-3} ft^3/hr	1.0×10^{-3}
Water Bubbling	1.0 cc/hr	3.5×10^{-5}
Micro Burettes	1.0×10^{-2} cc/hr	3.5×10^{-7}
Halogen-Type	1.0×10^{-6} cc/sec	1.3×10^{-7}
Mass Spectrometer	1.0×10^{-10} cc/sec	1.3×10^{-11}

Some calculations were made of measurement sensitivity required in order to permit total air leakages ranging from 10 to 1000 lb per year for a typical flight vehicle. Results of these calculations are presented in Table 6. As an example, it is assumed that 200 lb per year of air is an allowable leakage for a space vehicle. This represents a leakage rate of 0.298 cu ft/hr or 3.0×10^{-2} cu ft/hr for the leakage of each of ten sources in the cabin or 6.0×10^{-3} cu ft/hr for the leakage of each of fifty sources in the cabin. If this maximum leakage of each source is assumed to be measured by a technique with 100 graduations then the sensitivity of the measuring device is 1/100 of each or 3.0×10^{-4} and 6.0×10^{-5} cu ft/hr for ten and fifty sources, respectively. Obviously the allowable leakage rate will depend upon what portion of the total pay load of a particular vehicle may be devoted to the storage of air for cabin pressurization purposes. These calculations do not take into account air or oxygen that may be carried for breathing purposes.

To relate the figures of Table 6 to a known vehicle, the Mercury Space Capsule was selected. The allowable leakage rate for the Mercury Capsule is 300 cc per min (Ref. 7). The pressurized gas is oxygen; however, since there is little difference in the densities of oxygen and air this loss was not converted into equivalent air. The quantity 300 cc per min is equivalent to 0.63 cu ft/hr or, projected over a year, amounts to 470 lb of oxygen. Thus the allowable leakage rate of the Mercury Capsule, while appearing perfectly reasonable for as short a period as the 28 hours the capsule is expected to be in orbit, if applied to a vehicle that will be in orbit or on a mission for a period of one year, would result in a prohibitive amount of almost 500 lb of a gas merely to take care of leakage. Thus even as small an allowable air leakage rate as 10 lb per year does not require the sensitivity of a halogen leak detector for measurement purposes. However even such a small allowable leakage rate could not be called hermetic sealing. By way of caution it is pointed out that striving for hermetic sealing per se may impose weight penalties more prohibitive than those associated with provision of air for cabin leakage.

Table 6

ESTABLISHMENT OF ALLOWABLE LEAKAGE RATES

Total Allowable Air Leakage			Leakage of each of 10 Sources	Measurement Sensitivity	Leakage of each of 50 Sources	Measurement Sensitivity
(lb/yr)	(ft^3/hr)	(cc/hr)	(ft^3/hr)	(ft^3/hr)	(ft^3/hr)	(ft^3/hr)
470 (Mercury)	0.715	2.0×10^4	7.1×10^{-2}	7.1×10^{-4}	1.4×10^{-2}	1.4×10^{-4}
1000	1.49	4.2×10^4	1.5×10^{-1}	1.5×10^{-3}	3.0×10^{-2}	3.0×10^{-4}
200	0.298	8.3×10^3	3.0×10^{-2}	3.0×10^{-4}	6.0×10^{-3}	6.0×10^{-5}
100	0.149	4.2×10^3	1.5×10^{-2}	1.5×10^{-4}	3.0×10^{-3}	3.0×10^{-5}
50	0.075	2.1×10^3	7.5×10^{-3}	7.5×10^{-5}	1.5×10^{-3}	1.5×10^{-5}
10	0.015	4.2×10^2	1.5×10^{-3}	1.5×10^{-5}	3.0×10^{-4}	3.0×10^{-6}

V. PRELIMINARY INVESTIGATIONS

A. Special Investigations of Methods for Sealing Electrical Conductors

The leakage characteristics of insulated electrical wires were investigated in the laboratory. Several types of solid and stranded wire in several gages were potted through openings in the end of a small pressure chamber prepared from a 2-in. pipe nipple and two end caps. One of the end caps had openings through which the wires projected while the other was provided with a threaded pressure fitting. A pressure of 15 to 30 psig was exerted in the chamber to induce leakage along the wire, and the ends of the wires potted into and protruding from the chamber were submerged in water as a means of observing leakage. All of the stranded types of wire showed definite but varied amounts of leakage. The leakage appeared to be low when strands were tightly twisted and/or when fine wires comprised the strand. None of the several different solid wires so tested at pressures up to 30 psig gave any indication of leakage by this crude water bubble technique. A small cable consisting of four separate insulated stranded wires in one insulative sleeve offered practically no resistance to air flow.

Later some actual measurements were made of air leakage along commercial insulated stranded wires. A set of four wires, each consisting of No. 18 (16 strands) wire and insulated with a thin plastic tubing, leaked at a rate of approximately 1.0 cu ft of air per hour under a 15 psig pressure differential at room temperature, or at an average rate per wire of 0.25 cu ft/hr. A series of eight wires, consisting of No. 20 (nine strands) wire insulated with a plastic tubing plus the fiberglass jacket leaked at a rate of about 0.3 cu ft/hr at 15-psi differential and 0.5 cu ft/hr at a 30 psi differential or at average rates per wire of 0.04 cu ft/hr and 0.06 cu ft/hr, respectively. It was determined that in the latter wires, leakage occurs not only along the strands between wire and insulation but also between the tubing and the fiberglass insulation. Thus any sealing of these types of wires must also involve the area between layers of insulation.

Since stranded wire is obviously preferred over solid wire for use in air and space vehicles, it is essential that a satisfactory sealing method be developed. A two stage method for potting of stranded wires was investigated on this program. This technique involved stripping the wire for approximately 3/8 in. at about the plane of the cabin wall. The exposed strands were untwisted, separating the individual wires slightly. A few drops of a potting compound were applied to the bare wire and flowed between individual wires. After the compound was cured, the conductor was potted through an opening in the pressure vessel, fully encapsulating the wire over the length which was originally bared. Pressure tests of wire specimens so treated gave no indication of leakage under a pressure differential of 30 psi.

Three other techniques in addition to that described above were also investigated for sealing stranded wire. They include (1) slitting (instead of stripping) of insulation and potting, (2) potting through the insulation with use of a hypodermic needle, and (3) terminal potting of the conductors either by conventional means or with a hypodermic. For the hypodermic sealing technique, a very low viscosity for the potting material is important. Some of the liquid polymers can be made less viscous with suitable solvents but this usually has a negative effect upon cure, strength

adhesion and seal integrity. Consideration was given to the use of a potting material with good adhesion, such as an epoxy, rather than an elastomer with relatively poor adhesion, although both types were evaluated. Pressure tests on several insulated stranded wires indicated that the hypodermic sealing technique using epoxy resin as sealing material was fairly successful in preventing leakage along the wires under a 15-psi differential pressure. One wire specimen, however, was not satisfactorily permeated with the resin, as was evident from the lack of stiffness of the wire in the vicinity of the injection. This specimen leaked considerably during the test; one other leaked only moderately.

Several samples of insulated stranded wires were injected with an RTV silicone (Company A, Product No. 13) suitably reduced in viscosity with a thinner (Company A, Product No. 14). It was found that as much as 40 to 50% of thinner was required to permit injection of the fluid with a hypodermic using a No. 23 needle. The fluid was injected into the ends, middle and in slits in the insulation of the insulated wire samples. In some samples unthinned RTV silicone was applied to the slits in the insulation. The presence of a high percentage of thinner resulted in lowered physical properties of the cured silicone rubber as judged from control samples. Pressure tests were conducted on the treated wires. Some of the wires apparently had been sealed adequately because they gave no evidence of leakage under pressure differentials of 15 and 30 psi; however, others did leak. Although the results were inconclusive, it is believed that the low physical properties of the thinned RTV silicone used may have been responsible, through either poor adhesion or high permeability, for the leakages.

The wiring of sensitive instrumentation often requires that certain wires be shielded to prevent the pickup of stray signals. In space vehicles it is important that a means be provided for sealing all shielded cables so that air from pressure chambers cannot escape around or through these cables. To effectively seal such a cable requires that, without impairing the conductivity, insulation and shielding ability of the various components, an effective seal be introduced into the various passages. These include the spaces between the strands of each wire, between the various wires, between the wires and the shield, in between the mesh of the shield, and the outside of the shield.

An attempt was made to seal a shielded cable by stripping the jacket, shield, etc., until the individual wires were exposed. These, in turn, had segments of their insulation stripped from them on a staggered basis along the wire length and the wire strands were untwisted and separated. Using an RTV silicone as a potting compound the insulation was rebuilt in layers up to the cable's shielding. A new piece of expanded shielding was bridged over the built up segment and attached to one of the exposed ends of the original shielding by means of soldering. An additional quantity of the RTV silicone was poured into the open end of the new segment of shielding after which the shielding was pulled tight and the silicone was allowed to set. The remaining shield repair connection was made by soldering and the whole cable was encapsulated in another coating of the silicone.

In pressure testing the cable with its open end immersed in water, it was found that leakage, even though still present to an unacceptable amount, had been substantially reduced compared to an unaltered specimen. By sectioning the layer of encapsulating silicone it was found that a number of voids had been formed in the casting, thus making the seal ineffective. Time did not permit experimentation with different

casting techniques in order to optimize the process and produce an effective seal; however, it is believed that production of a seal of this type for a cable would be time consuming. Consideration was also given to injecting a resin hypodermically through the shielding and swaging the cable locally to squeeze insulation tightly around the stranded wires. This technique may have merit except for the deleterious effect which it may have upon the shielding. Two attempts were made at swaging a shielded cable without first locally injecting a resin. These were (1) the use of a hose clamp tightened around a piece of plastic tubing around the cable and (2) the use of a copper tube swaged crudely by hand around the piece of cable. Neither technique was satisfactory in blocking the passage of air along the cable as evident from the water bubbling pressure test. No further electrical wire sealing concepts were investigated.

B. Investigation of Permeability of Elastomer Materials

Diffusion theory is based upon the work of Adolph Fick, first published in 1855 (Ref. 8). This theoretical work preceded any quantitative experimental work in the field. Fick's first law states that the quantity of diffusing substance which passes per unit time through unit area of a plane at right angles to the direction of diffusion, known as the flux, J, is proportional to the concentration gradient of the diffusing substance. Representing the concentration, or amount per unit volume, as C and taking the X direction to coincide with the direction in which diffusion occurs, Fick's first law (Ref. 9) may be written:

$$J = -D \frac{dC}{dx} .$$

The factor D, known as the diffusivity or diffusion coefficient, is introduced as a proportionality factor with the dimensions of $(\text{length})^2/(\text{time})$.

Fick's second law is derived from the first by considering that the rate of accumulation of diffusible substance in a given volume element is the difference between the inward and outward flux. D is considered to be constant (at constant temperature) and diffusion is considered to be taking place in a single direction. Fick's second law may be stated as follows:

$$D\nabla^2 C = \frac{\partial c}{\partial t} .$$

Much of the theoretical work on diffusion has been concerned with the solution of this partial differential equation.

Extensive measurements of the permeability of various polymers and also metals and non-metals have been made by Amerongen (Ref. 10). Based on these results, it appears that permeation is a process in which gas molecules dissolve in the solid on one side of the membrane, diffuse through to the other side and evaporate. The permeability can be calculated from measurements of solubility and rate of diffusion. The rate of diffusion of a gas in a given polymer is found to be related chiefly to the size of the gas molecule. The presence of polar groups or methyl groups in a polymer molecule reduces the permeability to a given gas. Consequently, the nitrile rubbers and butyl rubber have low values of permeability (Ref. 11).

By solving Fick's second law for the passage of gas through a membrane initially containing no dissolved gas, and assuming a concentration-independent diffusion coefficient, one can obtain the number of moles of gas passing per unit time through a membrane of thickness L and area A when the pressure differential of the gas across the membrane is ΔP. Thus

$$\frac{dn}{dt} = Q \frac{A}{L} \Delta P \quad .$$

The quantity Q is a constant of proportionality called the permeability constant of the membrane with respect to the given penetrant gas (Ref. 12).

In the preceding discussion, diffusion was treated for membranes, that is, relatively thin materials. Usually permeability of materials are measured and reported for thicknesses of 0.025 in. The applicability of such data to thick sections and in particular the applicability of the permeability formula in which diffusion of a gas through a material is inversely proportional to the thickness of the material was questioned. Therefore a series of experiments was undertaken to verify the linear dependence of permeability on material thickness.

It was intended that permeability tests would be performed on three thicknesses of material ranging from 0.025 in. through 1/16 in. in order to determine the applicability of the permeability data obtained from tests of 0.025 in. samples to thicker sections. Because of time limitations only two thicknesses were examined. They included the 0.025 in. and a 0.057 in. sample. Because of their high permeability and also because of their potential usefulness on the program a silicone elastomer material was chosen. The particular silicone was Company A, product No. 1. The apparatus used for determination of the permeability of silicone rubber consisted of a glass vacuum system with a manometer and a stainless steel permeability cup. A standard taper joint (stainless steel to glass) connected the cup to the glass system. The area of permeability measurement was approximately 1 sq in. The sample disc was inserted in the permeability cup and was held by a heavy flat ground stainless steel washer. A heavy threaded stainless steel plug was then turned down on the washer. A recessed O-ring provided a seal between the plug and the washer. The plug contained a central hole to provide atmospheric pressure on one side of the sample.

Two samples of 0.024 in. thick product No. 1, cured 24 hr at 480°F, averaged 3.2×10^{-7} cc/sec/cm^2/cm for a one atmosphere pressure differential at room temperature. The permeability test of the thicker (0.057 in.) sample of product No. 1 resulted in a permeability coefficient of 3.0×10^{-7}. This value compared fairly well with the average of the two 0.024-in. thick specimens. The slight difference can be attributed to variations in atmospheric pressure during the experimental runs and to possible experimental error. After making barometric corrections it was found that the permeabilities were comparable. This verified the linear dependence of permeability on thickness.

VI. SEAL MECHANICAL DESIGN CONCEPTS

A. Rotating Shaft Seal Concept

Under the assumption that a rotating shaft passing through the cabin wall may be subject to continuous operation at a rotational frequency of 500 rpm for a period of one year, a concept for a rotating shaft seal was devised. In utilizing the shaft to activate a control or operate a device, the exact shaft placement and alignment would be determined by bearings located remote from the cabin wall. As a result, the seal between the wall and the shaft must adjust to the alignment and position of the shaft. Since the seal effectiveness and life span are adversely affected by any side thrust between the shaft and the seal, concentricity of the two is required and should be maintained. In addition, it is necessary to provide a film with lubricating qualities between the shaft and the seal; otherwise the rubbing action would cause abrasion of the sealing surfaces and result in early failure.

The rotating shaft seal concept developed on this program is shown in Fig. 1. It utilizes a pair of flexible bellows type diaphragms to give the seal a floating action or the ability to conform to initial shaft misalignment and to maintain proper alignment and concentricity in spite of the dynamic loads that may be applied. Standard lip seals are shown with garter-like retainers in conjunction with an Oilite type porour sleeve bearing and lubricant reservoir. Should retention of the lubricant prove impossible because of the pressure differential existing between the seals, and in particular because of the high vacuum condition on one side of the seal, a dry solid film lubricant such as molybdenum disulfide may be utilized applied to either the bearing surface or the shaft. Such lubricating films produce higher friction than liquid lubricants, but are the only lubricants that retain integrity under high vacuum and extreme temperature conditions.

B. Reciprocating Shaft Seal Concept

Operating conditions anticipated for the reciprocating shaft were as follows: The shafts are to be subjected only to true reciprocation with no rotation. The short stroke shafts, with strokes of the order of 3 in., may operate at 20 cycles per second for 8 to 12 hrs per day, while the long stroke shafts, with strokes of the order of 36 in., will operate with low frequency. The same conditions regarding shaft misalignment as were considered for the rotating shaft were considered here. The developed concept for the reciprocating shaft seal is shown in Fig. 2. Here a floating seal retainer with a spherical seat and corrugated garter spring were employed to assure alignment and concentricity even under vibration and shock loadings. A more rigid structure is required than for the rotating shaft seal because of the drag effect of the seals on the reciprocating shaft. Several conventional O-ring seals are shown in conjunction with an Oilite type porous sleeve retainer-bearing combination and lubricant reservoir. This method of lubrication is less likely to be employed, than in the case of the rotating shaft, because too much lubricant would be lost at the vacuum side of the bearing. Again a solid film lubricant was considered especially for the high temperature situation. The space occupied by the corrugated garter spring, in addition, could be filled by a hydraulic fluid to aid in damping shaft vibration and to allow the bearing and seal to adjust to the shaft location. To protect

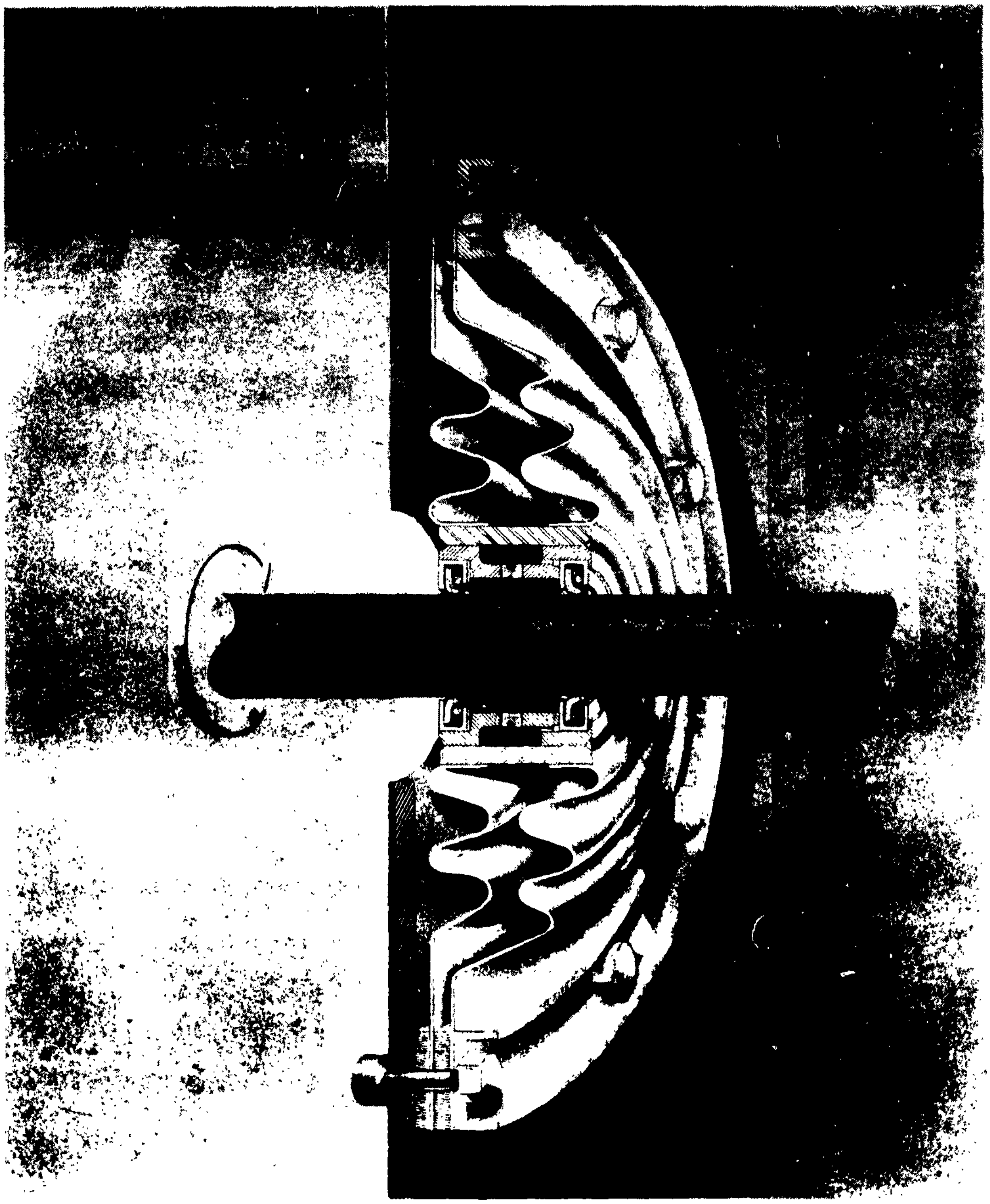


Figure 1. Rotating Shaft Seal

Figure 2. Reciprocating Shaft Seal

the shaft from the abrasive effect of dust and dirt a dust cover (not shown) may be employed on both sides.

C. Hatch and Escape Door Seal Concept

For hatch seals, the size of the opening considered was that permitting an occupied ejection seat to pass through for emergency purposes. An outward opening hatch with some parallel movement prior to rotation about a hinge was considered necessary for emergency escape especially in a reentry vehicle with inner and outer cabin walls. A reusable seal was considered desirable but an expendable seal would be acceptable provided that the installation and replacement were kept relatively simple. Since the seal was to be near absolute and fail safe, the conventional diaphragm seals, inflatable seals, and mechanical crush-up or gasket seals did not appear to be adequate. A hatch seal concept conceived to accomplish these requirements is shown in Fig. 3. The seal design in theory presents multi-point contact, which could be quite effective in sealing an escape hatch as well as in permitting easy open-close action and continued reuse.

D. Electrical Cable Seals

The insulated stranded wire sealing concept developed is shown in Fig. 4. The preliminary investigations of electrical wire sealing reported in Part V of this report provided the basis for development of this concept. The concept involves local stripping of the insulation and untwisting the strands slightly to separate them and allow resin to penetrate. The wires are placed through a metal retainer, and an elastomeric potting compound is cast around the bundle of wires. The resin permeates the wire strands and upon curing should effectively block air flow along the wires. The complete potted joint can then be placed into and bolted to a hole in a cabin wall. A thickness of elastomer beyond the flange of the metal retainer, with an adhesive, permits sealing the bolted attachment.

Some alternative wire sealing techniques which were investigated are shown in Fig. 5. They included hypodermic potting somewhere along the length of the wire, preferably at the cabin wall; terminal hypodermic potting, that is injecting resin at the end of the wire on the pressure side; and slitting the insulation locally instead of stripping the insulation as was shown in Fig. 4. Each technique would additionally require potting the bundle of wires or cables at the cabin wall with a suitable elastomer in a method similar to that shown in Fig. 4.

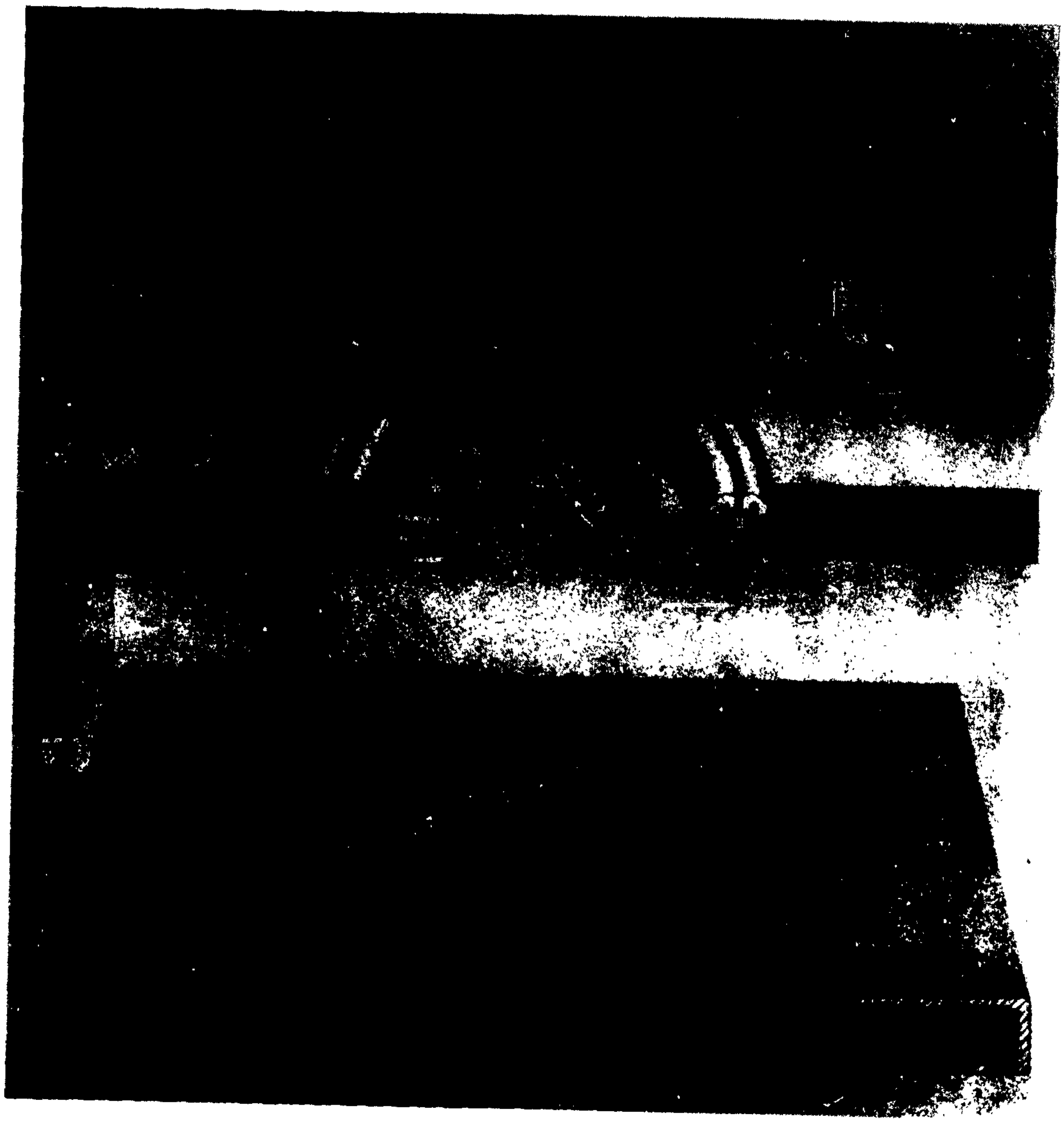


Figure 3. Escape Hatch Seal Concept

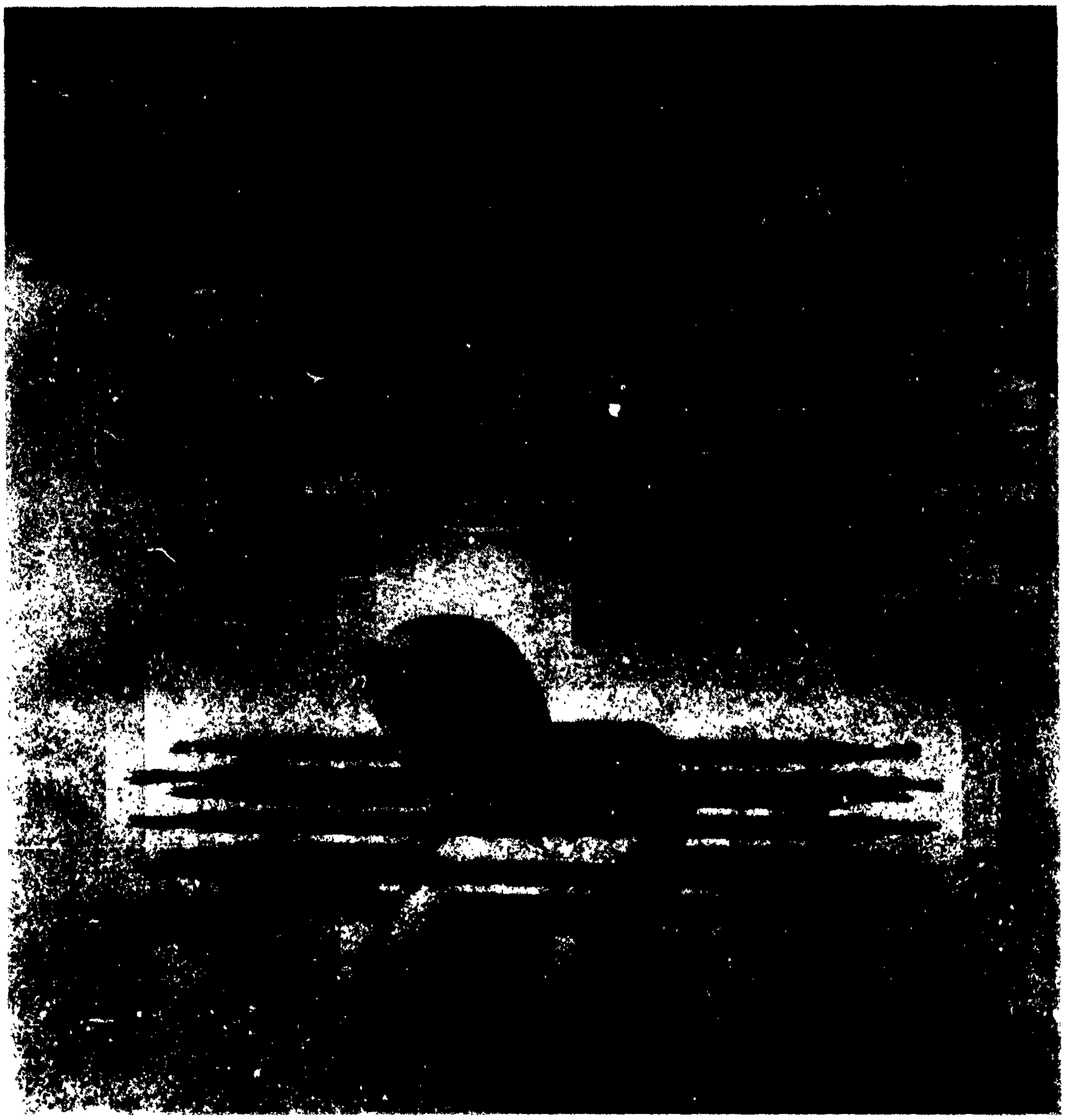


Figure 4. Insulated Wire Seal and Potting Concept

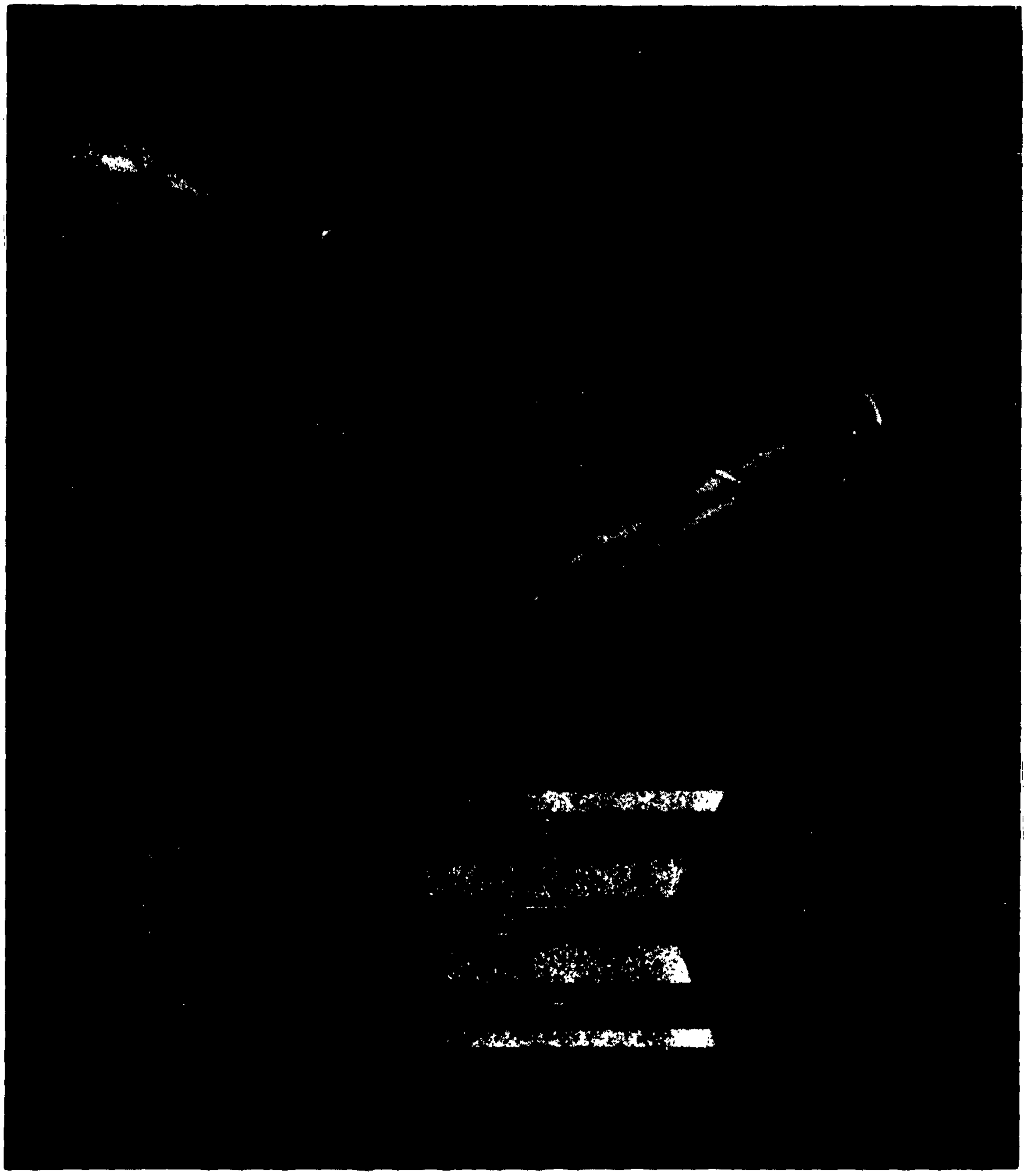


Figure 5. Additional Wire Seal Concepts

VII. SEAL FABRICATION

A. Rotating Shaft Seal

All of the metallic components of the rotating shaft seal concept were fabricated with an aluminum alloy. A cross section drawing showing design details of the rotating shaft seal is given in Fig. 6. The unique feature of this concept, the corrugated flexible diaphragms, required considerable development work in order to perfect the design. Originally it was contemplated that the diaphragms would be fabricated from a 0.005 to 0.010 in. thick spring tempered sheet stock. Using a metal spinning process, the fabricator found it impossible to fabricate the diaphragms from such a thin material. Instead several diaphragms were fabricated from 0.020 in. stock in an aluminum alloy, a copper, and in a brass alloy. The diaphragms so fabricated were found to be much too rigid for the application. That is because of the inherent stiffness of the combined thickness and corrugation the diaphragms would not permit transverse displacements under loads approximating those which might be experienced by a misaligned shaft. Therefore alternative methods of fabricating the diaphragms were investigated. Several attempts were made to fabricate the diaphragms from a porous metal network such as woven wire or screen coated with an elastomer. Some diaphragms were made fairly successfully from a wire screen impregnated with an RTV silicone. However, the silicone rubber diaphragm appeared to be too flexible for its intended purpose even with the wire fabric reinforcement. The high permeability of silicone rubbers would also prevent utilizing them for this application. Other materials such as epoxy resin with a lower permeability and greater rigidity were considered but were not utilized. Another disadvantage of a wire fabric-rubber diaphragm would be its inability to withstand a 1 atmosphere pressure differential without crushing.

Development activities turned toward utilization of the metal diaphragms previously spun from the 0.020-in. thick material. Consideration was given to reduction of the thickness by a chemical milling process but this was never attempted. Instead, attempts were made to reduce the thickness by a mechanical machining process. But the procedure resulted in a non-uniform reduction of the thickness and consequent damage to the diaphragms. The next attempt was one which gave promise of being the most successful and producing diaphragms with enough flexibility to permit alignment of a shaft and to damp out any transverse vibrations and shocks which might be incurred by the shaft. This development follows.

The existing thick diaphragms were slotted with 12 slits from the center radially out to the outer rim but not through the rim. The resulting slits were bridged with a viscous elastomer material which becomes rubber-like on curing. An RTV silicone was used for the extreme temperature environment while a Thiokol base RTV material (which cures rapidly under heating) was used for the moderate temperature range. The resulting diaphragms were integral and relatively impermeable units with series of interconnected spokelike members each of which deflect under load. Excessive deflection would be avoided by attachment to neighboring spoke members through the bridging elastomer material. When each set of these diaphragms was completed it was judged that they would be capable of the proper amount of stiffness to effect alignment of the rotating shaft and to maintain seal effectiveness at all times in spite of transverse vibrations and other disturbances.

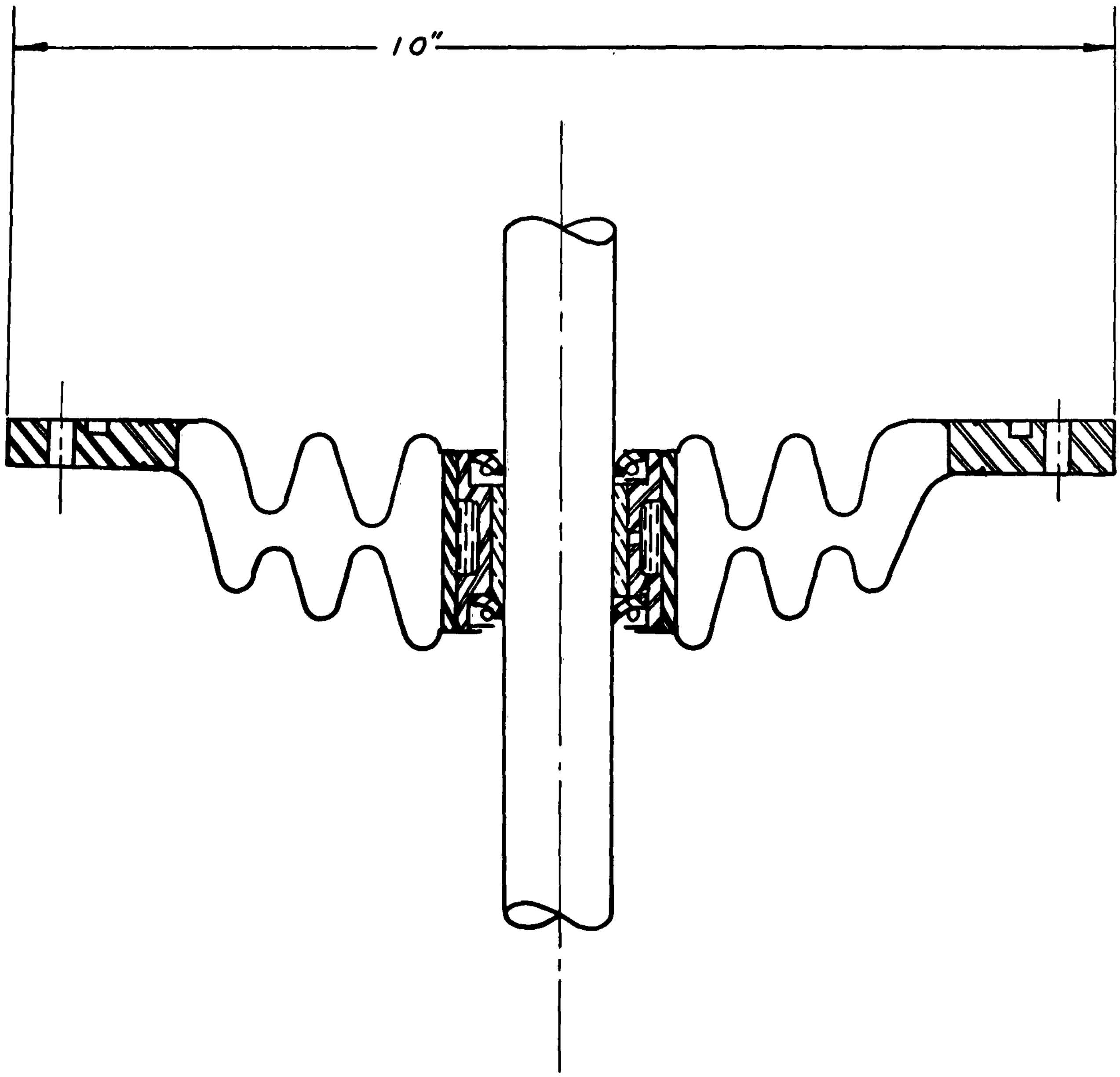


Figure 6 Design Details of Rotating Shaft Seal

Special precautions were taken in the assembly of these diaphragms to the hub containing the lubricant reservoir and bearing. However, in spite of these precautions while the attachment was successfully made by welding with the diaphragms bridged with the RTV silicone material, successful results were not obtained with the diaphragms bridged with the RTV Thiokol material. In welding of these latter diaphragms the diaphragm and hub combination was damaged beyond repair and thus was not available for testing.

Photographs of the completed rotating shaft seal concept are given in Figs. 7 and 8. Figure 7 shows the vacuum (outside) side of the seal with a shaft in place. Details of the diaphragm and the silicone rubber covered slits are quite evident in the photograph. The welds attaching the diaphragm to the hub and to the outer rim of the assembly have been machined to permit flush mounting in the test fixture. An O-ring groove was provided to effect sealing of the assembly. The reverse or pressure side of the assembly is shown in Fig. 8. Of particular interest in this photograph, besides the details of the diaphragm, is the conventional lip type seal. Shown in Fig. 8 is the Company B seal product No. 2. The other type of lip seal employed was Company B seal product No. 3 also with metallic parts of stainless steel and the sealing element of Teflon. The bearing housing was fabricated from two concentric cylindrical aluminum members hollowed out to permit storage of a lubricant in the hollow portion. Holes were provided on the inner wall of the housing to permit flow of the lubricant into the porous oilite type bearing inserted inside the inner cylinder. For extreme temperature situations where a liquid lubricant would be incapable of providing effective lubrication, because of either freezing or heat deterioration, an alternate non-porous solid bronze bushing was also provided. Lubrication under such circumstances would be provided by a dry film lubricant applied to the shaft. On this program the application consisted of a Company C product No. 4.

B. Reciprocating Shaft Seal

The components of the reciprocating shaft seal were also fabricated from an aluminum alloy with the exception of all of the elastomeric O-rings employed. A cross sectional drawing giving details of the reciprocating shaft seal is given in Fig. 9. Basically from the shaft outward the concept consists of the following: a porous oilite type bearing with three parallel O-ring grooves in the inside diameter for housing the dynamic O-ring seals. The bearing is press fit into a hollow hub constructed from two cylindrical members welded together. The external periphery of the hub is spherical in cross section. Extending outward from the hub is a spherical seat constructed of two flat disc-like members bolted together each containing an O-ring groove at the outer periphery on the outside and the vacuum side surfaces. This latter member fits into a larger outer ring with a recess 0.002 in. deeper than the thickness of the mating member. A ring-like cover fitting over the two members completes the assembly. The O-rings shown serve to seal all of the mating members. The recess in the large outer ring is considerably larger than the diameter of the member serving as the spherical seat for the hub. Lateral displacement of this member accommodates shaft misalignments to maintain seal effectiveness in the event of transverse vibrations or shock loadings experienced by the shaft. The concept as shown is designed to be installed on the pressure or inside side of a vehicle cabin. However, during evaluation testing the seal was installed on the outside or vacuum side of the chamber. Shown also in Fig. 9 is a

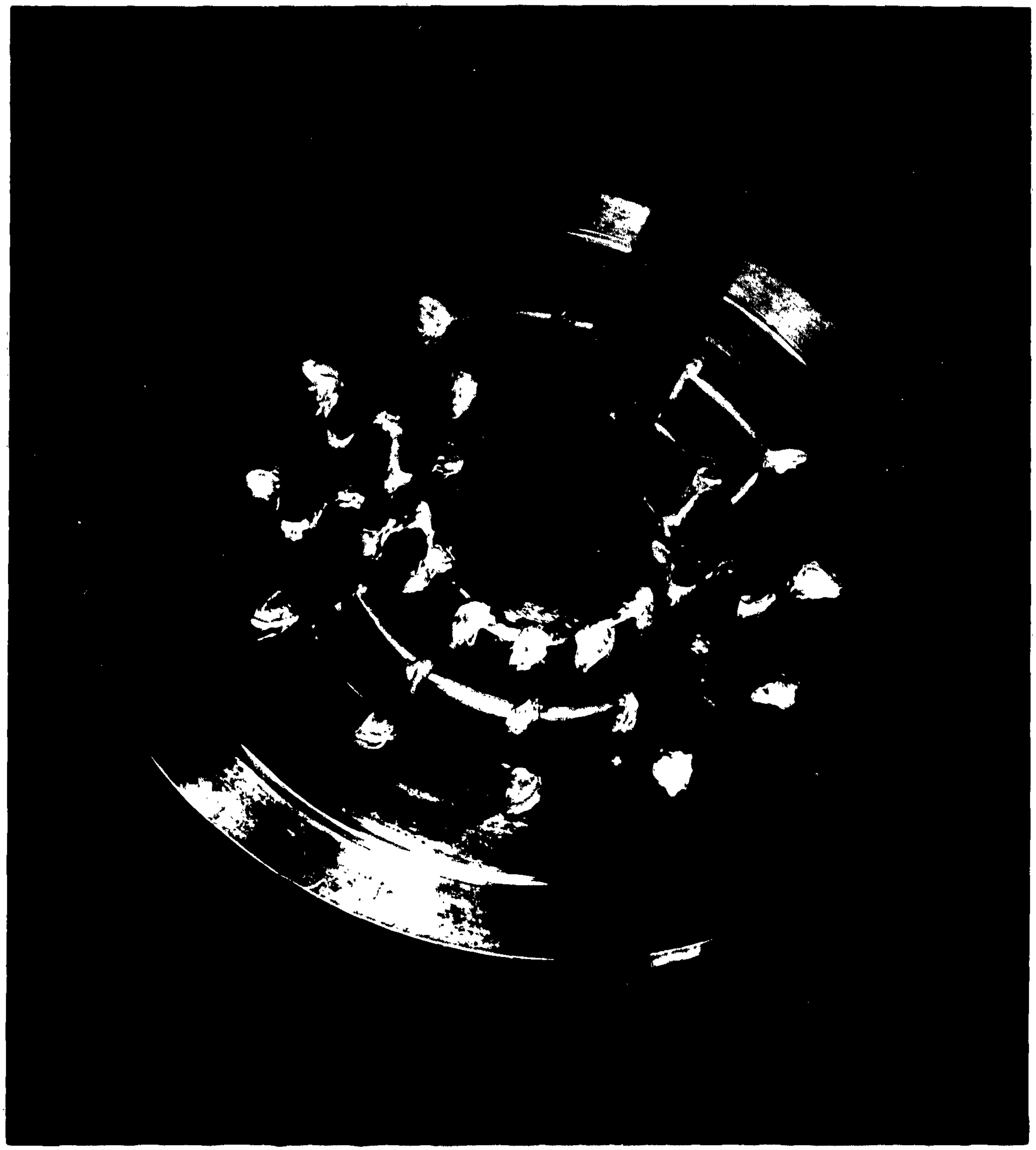


Figure 7. View of Outer (Vacuum) Side of Rotating Shaft Seal Assembly

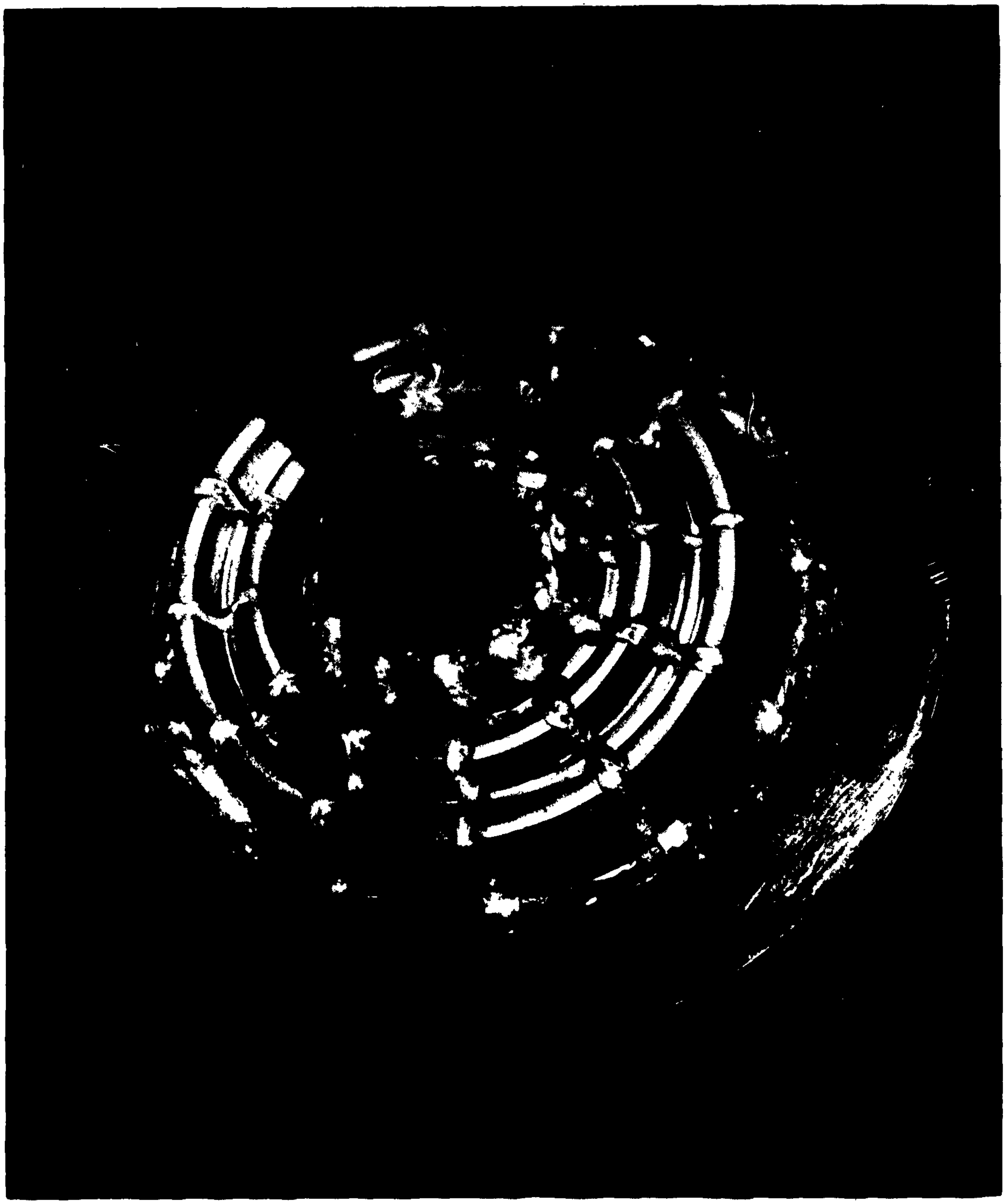


Figure 8. View of Inner (Pressure) Side of Rotating Shaft Seal Assembly

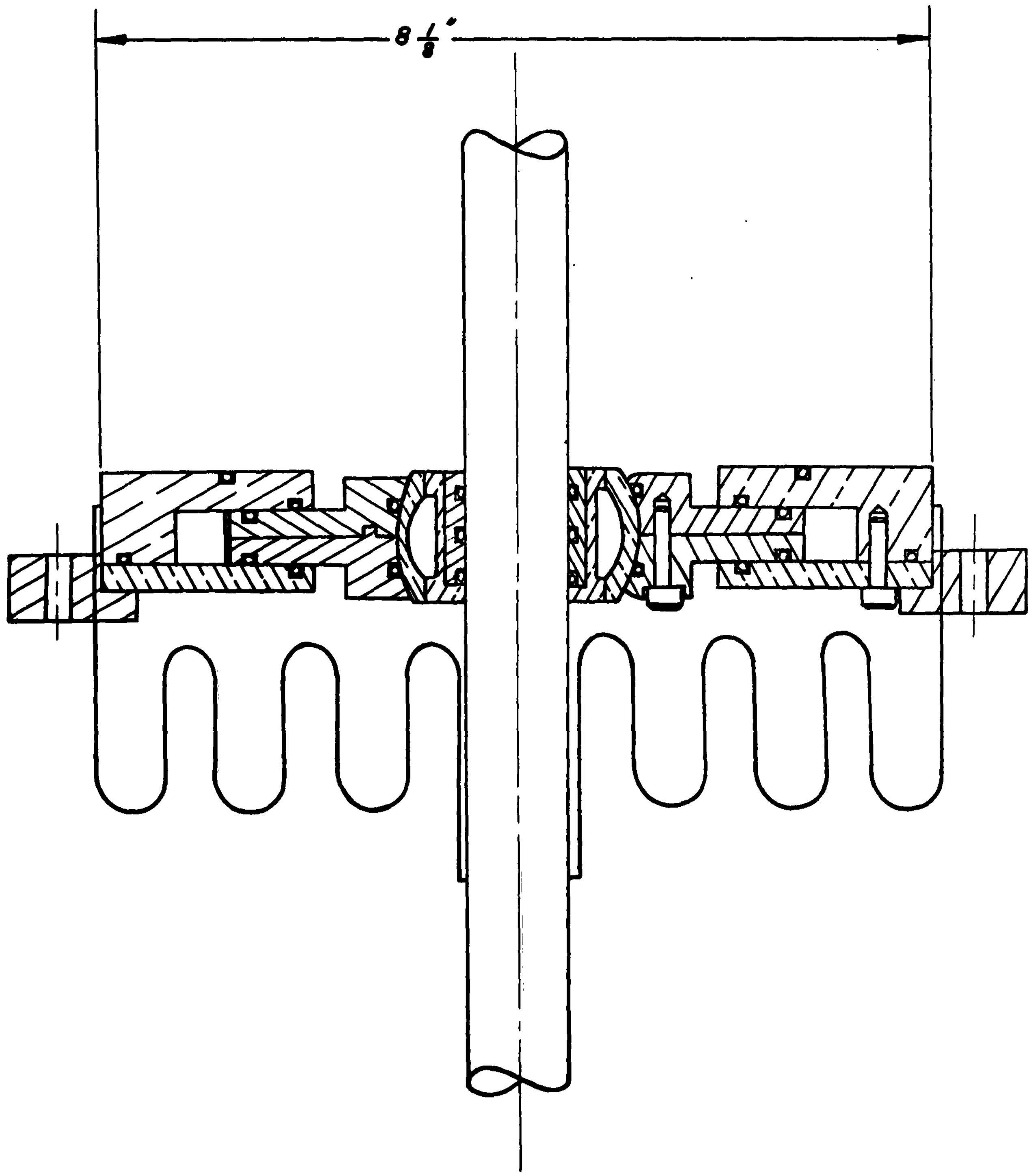


Figure 9 Design Details of Reciprocating Shaft Seal

dust cover for protection of the shaft during reciprocations. A dust cover was not fabricated on this program. An alternative non-porous solid bronze bushing was also provided for this concept to be used in conjunction with a dry film lubricant coated shaft for the extreme temperature conditions. Another reason for providing the alternative bearing lubrication system was the fact that the O-ring elements, in particular the dynamic O-rings in contact with the shaft, were a silicone rubber compound. The resistance of silicones to liquid lubricants, especially of the silicone fluid type, is very poor. Hence the use of a dry film lubricant was indicated. The O-rings utilized for the Phase I temperature range were a Buna-N material, Company D product 5; while for the Phase II sealing application the O-rings were a silicone, Company D product 6.

A photograph of the reciprocating shaft seal assembly with the cover plate removed is shown in Fig. 10. All of the O-rings are shown in place. It is easily seen that the center assembly is free to move laterally in the outer member. A portion of the spherically seated central hub containing the bearing and the shaft O-rings is also visible. A photograph of the assembled reciprocating shaft seal with a shaft in place is given in Fig. 11. Shown is the vacuum side of the assembly. It should be noted that the hub is designed so as to completely shield the bearing and shaft O-rings from direct exposure to thermal and nuclear radiation and vacuum environments.

C. Hatch Seal

A conceptual drawing for an outward opening escape hatch and seal is given in Fig. 12. Shown also is a concept for an opening and latching mechanism. In operation the hatch would open straight outward until the seal is cleared and then would swing to one side. A drawing of the actual seal developed for this hatch sealing application is given in Fig. 13. The actual hatch seal fabricated for evaluation on this program was modified slightly from the concepts shown in Fig. 3 and 12. Modifications were made primarily to facilitate fabrication of the seal. The seal prototypes were molded using a specially developed mold by Company E.

The seal design is based partly on the unsupported area principle. With the use of an appropriate depressor as shown in Fig. 12, when the hatch cover is closed the depressor makes contact with the seal at five points, and, therefore, in effect there are five sealing surfaces. It was intended that the seal be seated in a channel with the use of an adhesive to prevent leakage between the seal and the retainer. However for test purposes on this program, because of desire for evaluating three different seal materials under several temperature conditions, it was necessary to eliminate the adhesive. Instead the base of each seal fitting into the seal retainer was coated with a suitable high vacuum grease when installed for test purposes. The three materials employed in the fabrication of the seals were (1) a butyl (Company E product No. 7), (2) a Hypalon (Company E product No. 8), and (3) a silicone (Company A product No. 9). The butyl material was chosen because of the extremely low permeability characteristics of butyl. It was intended for room temperature testing only in which comparisons could be made of the effect of permeability of the seal material upon total leakage. The Hypalon material was intended for the Phase I application while the silicone material was intended for the Phase II application. A photograph of two of the hatch seal prototypes is given in Fig. 14. The Hypalon seal is on the left and the silicone seal is on the right. A drawing giving details, including

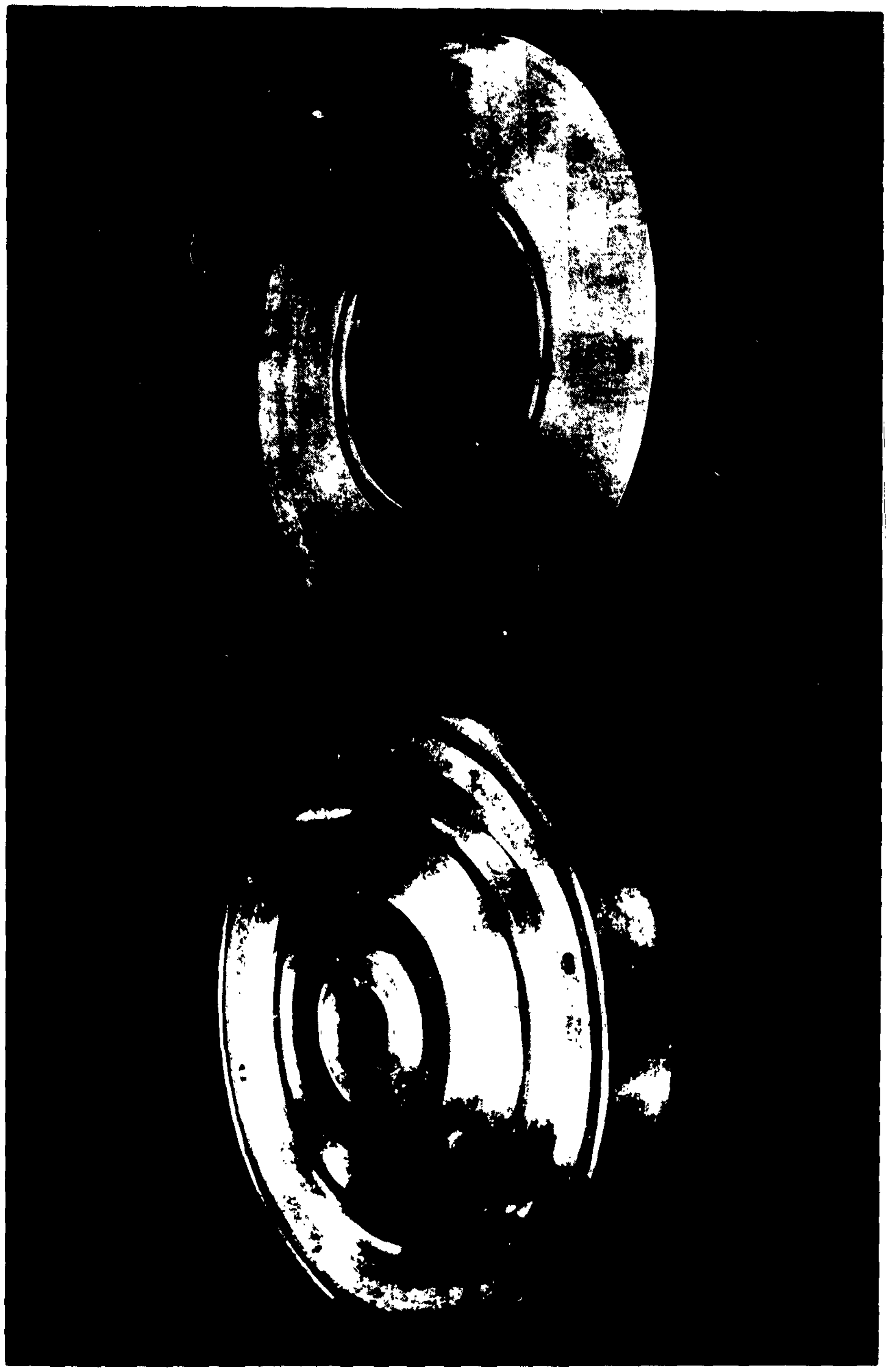


Figure 10 View of Rotating Shaft Seal Assembly with Cover Removed

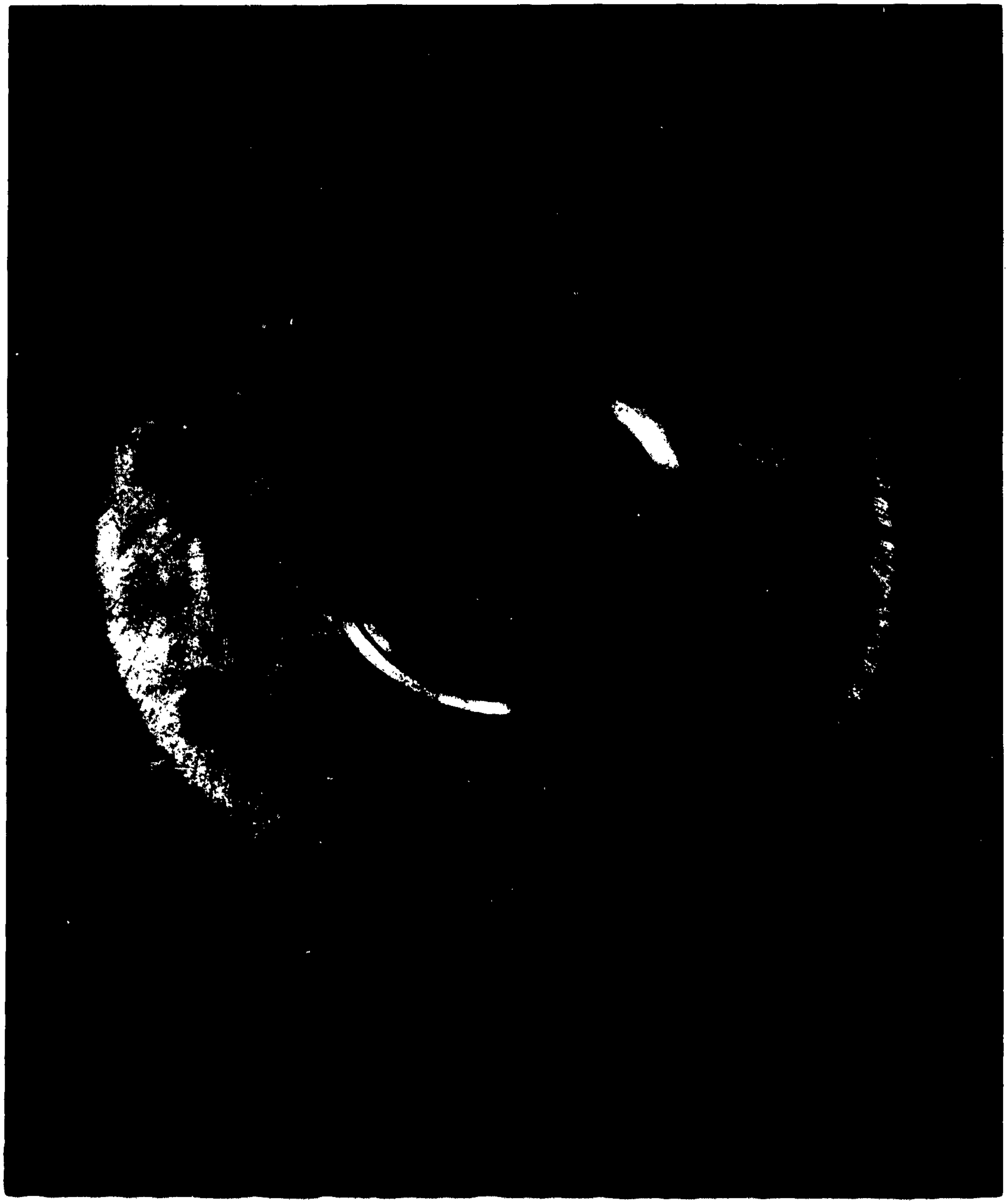


Figure 11. View of Outer (Vacuum) Side of Reciprocating Shaft Seal Assembly

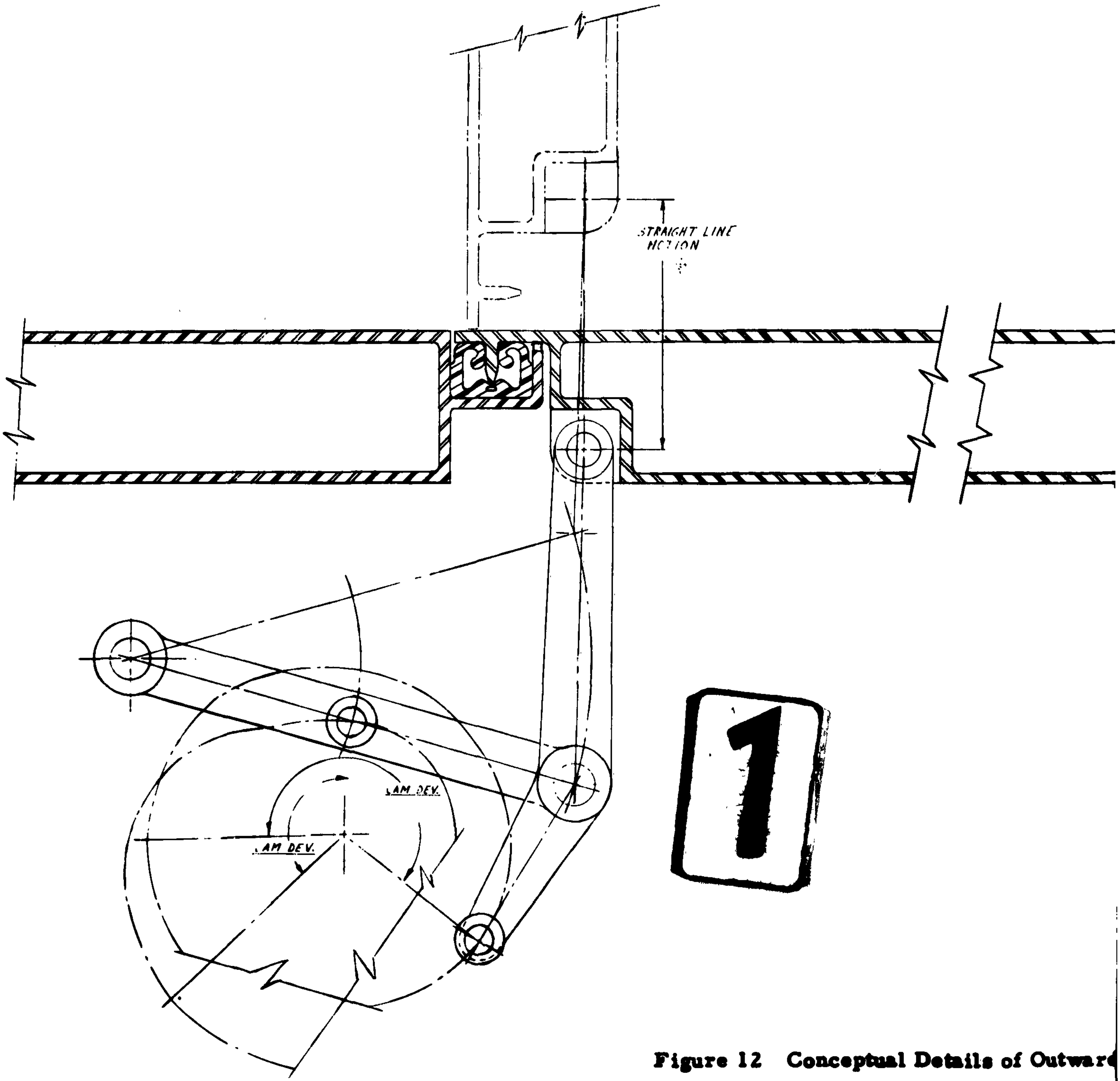
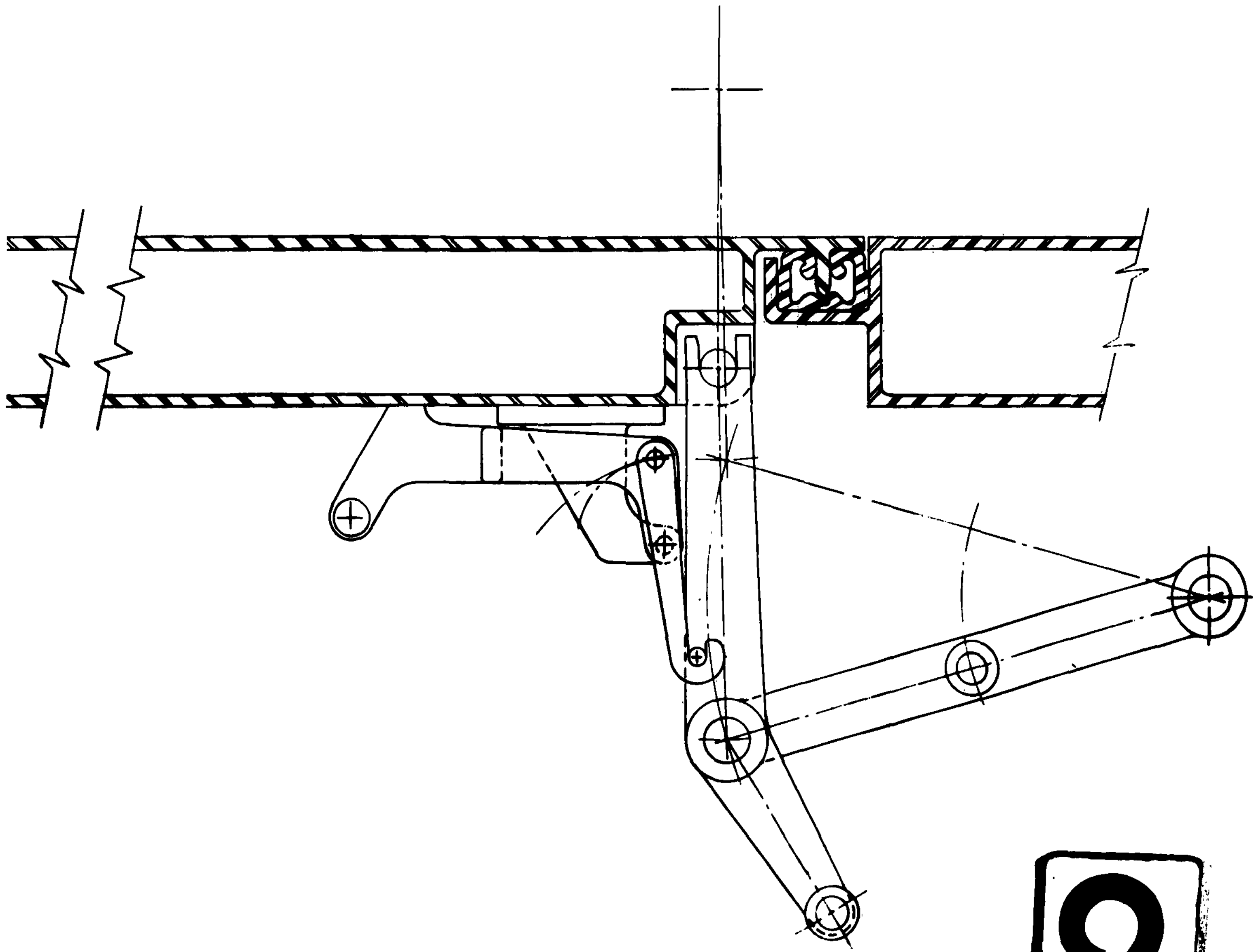


Figure 12 Conceptual Details of Outwar



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ual Details of Outward Opening Hatch and Seal

the depressor, of the hatch cover plate is given in Fig. 15. The cover was made from several type 304 stainless steel components welded together. For the purposes of the test program the cover was affixed to the interior of the chamber by means of bolts for which 18 holes around the periphery were provided.

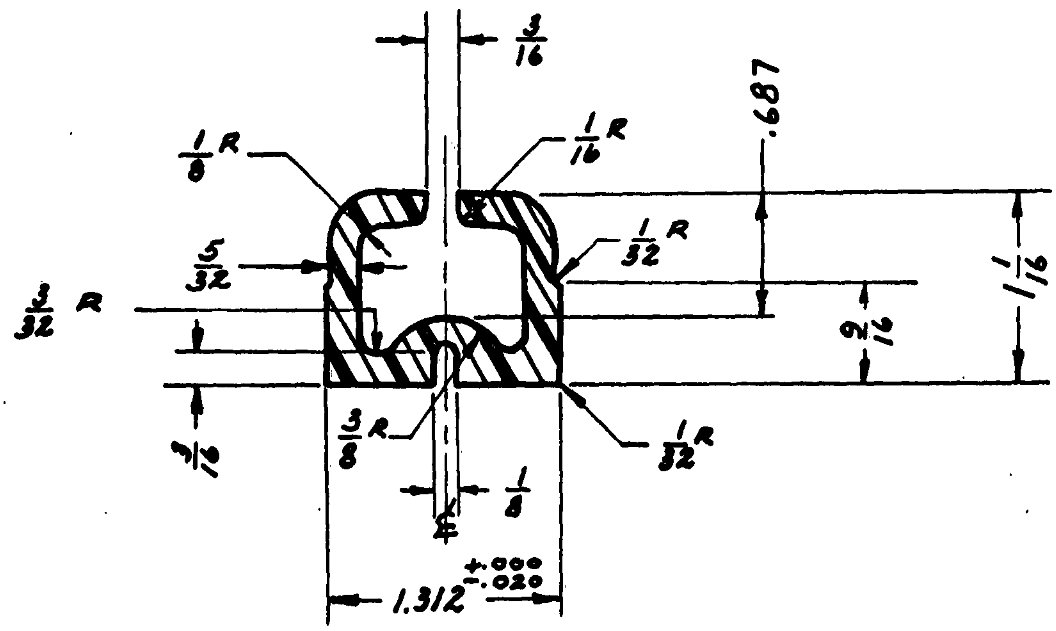

Figure 13. Design Details of Hatch Seal

D. Electrical Conductor Seal

In Fig. 4 details of the electrical conductor seal concept are shown better than any line drawing could provide. Fabrication of the seal was as follows: a circular disc-like plate with flange was drawn using a special die. The material was a 2024 aluminum alloy. Two thicknesses were used (0.031 and 0.063 in.). Six holes were punched around the periphery of the disc in order to facilitate mounting. Nineteen holes were punched and dimpled in a cluster around the center of the disc. Individual pieces of No. 18 insulated stranded wire each of which had a portion of the insulation stripped away for approximately 1/2 in. were inserted in the small holes in the center of the disc. A photograph of one of the discs and several of the stripped as well as unstripped sires is shown in Fig. 16. Components of a specially developed mold for potting the wires are shown in Fig. 17. A view of the wire-disc combination ready for potting is shown in place in the open mold in Fig. 18. Potting was accomplished by pouring a liquid RTV elastomer into the mold through a specially provided opening as shown in Fig. 19. The materials employed were as follows: for the Phase I application the wires had a thermal plastic insulation and the potting compound was a Company F product No. 10 compound. For the Phase II application the wires had a Teflon insulation and the potting compound was Company A product No. 11. Both potting compound materials required the addition of an appropriate catalyst to effect room temperature curing. The latter potting compound (product No. 11) required vacuum de-airing both after mixing and after molding to assure removal of all entrapped air. Two views of the completed electrical conductor seal assemblies are shown in Fig. 20.

Figure 14 Actual Hatch Seals: Hypalon (left) and Silicone (right)

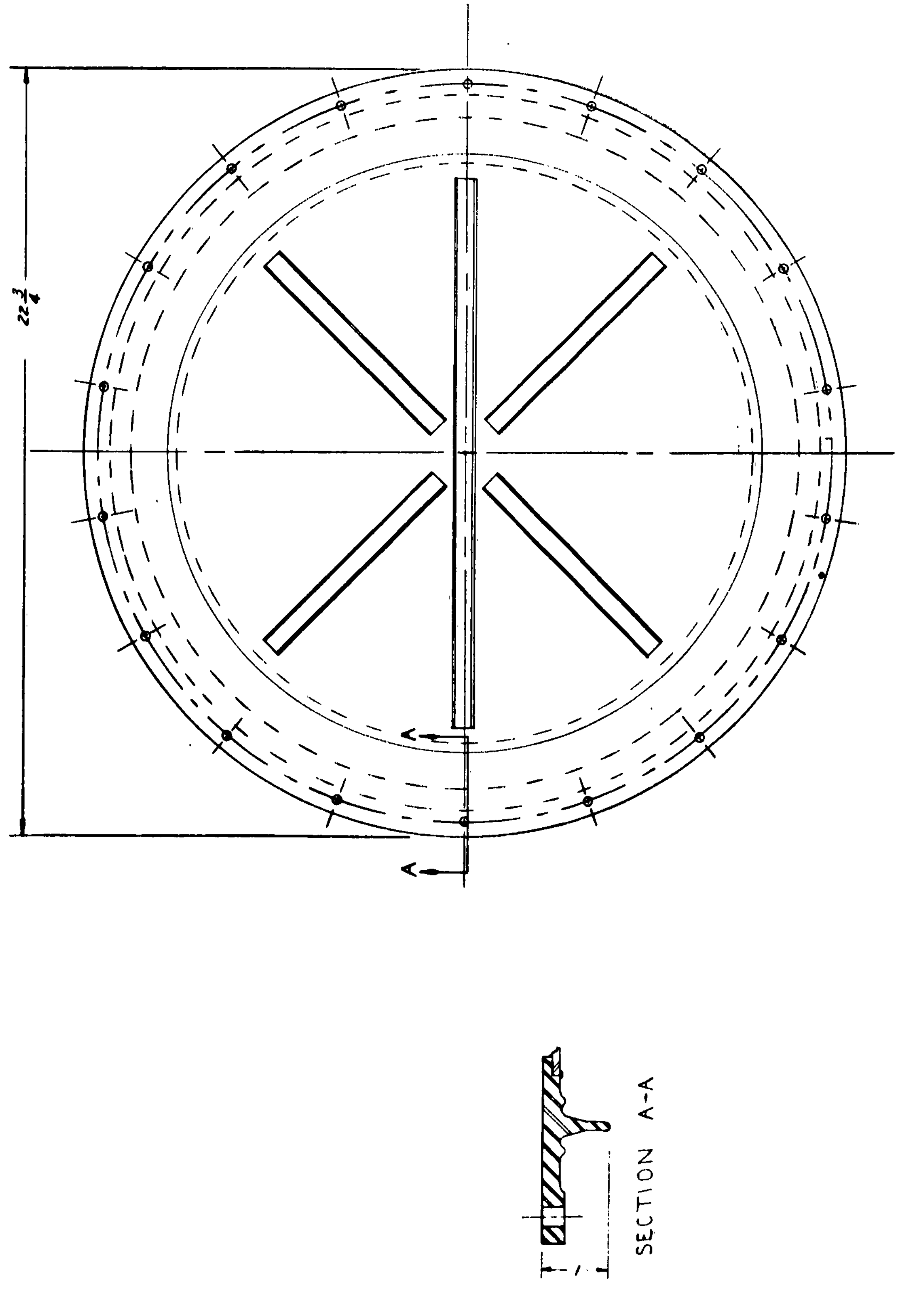

Figure 15 Design Details of Hatch Cover Plate

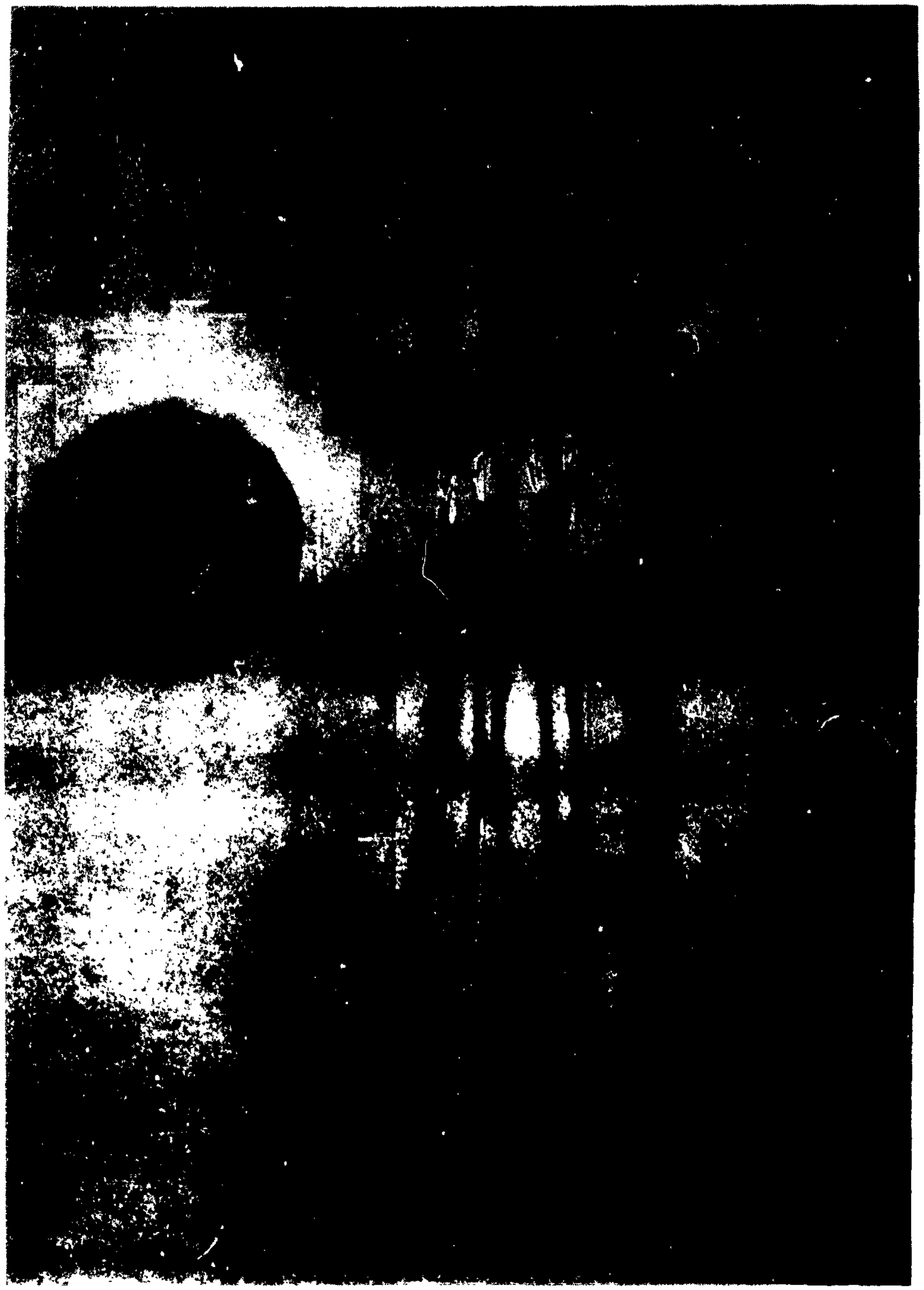

Figure 16 Stripped and Unstripped Insulated Wires and Aluminum Disk

Figure 17. Mold Parts for Electrical Conductor Seal Fabrication

Figure 18. Open Mold Showing Stripped Wires and Disk Ready for Potting

Figure 19. Closed Mold Showing Pouring of RTV Silicone Potting Compound

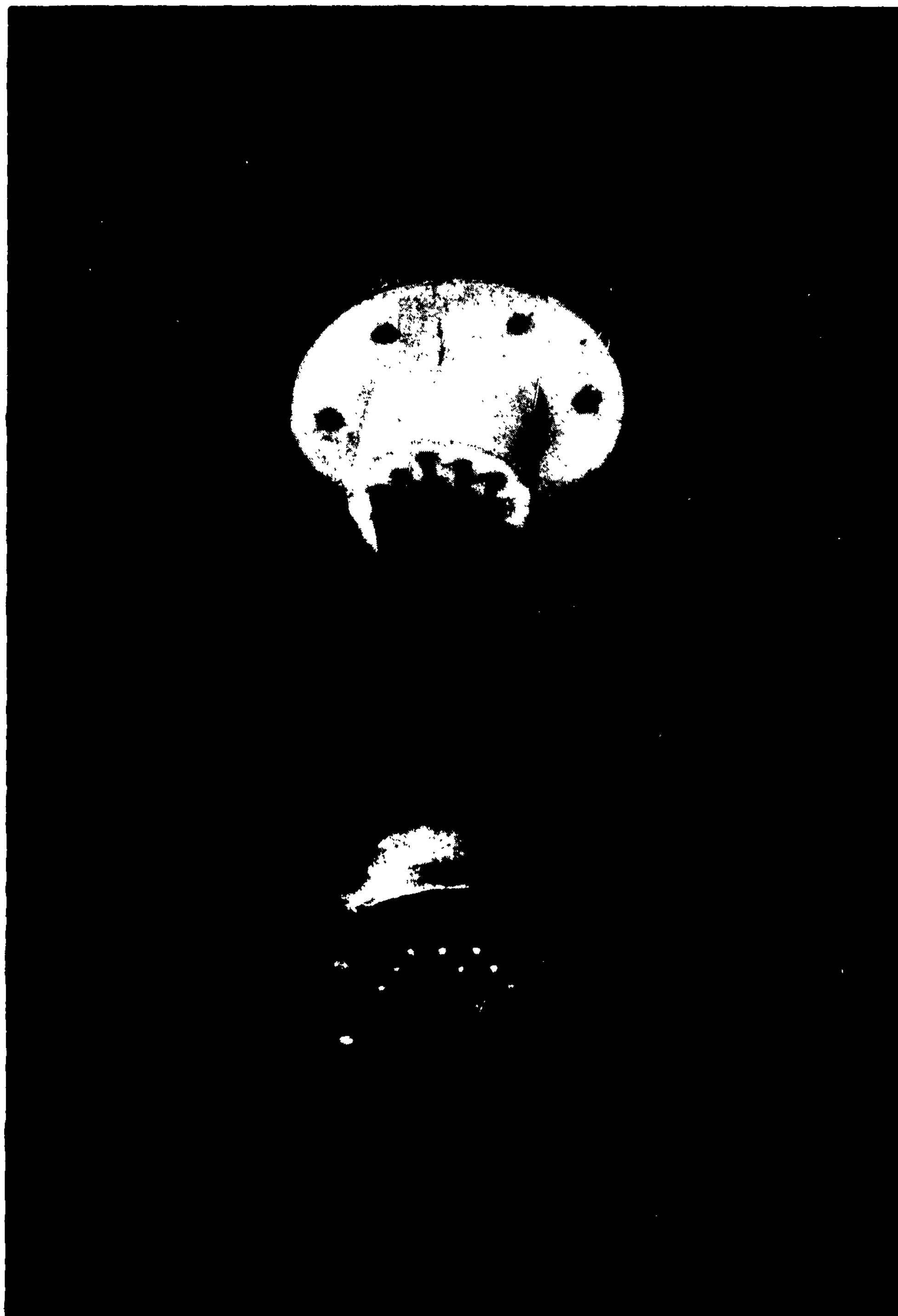

Figure 20. Two Views of Completed Electrical Conductor Seal

VIII. EVALUATION OF THE SEAL CONCEPTS

The four developed seal concepts were evaluated in a comprehensive series of tests under combined high vacuum and temperature conditions. The Phase I seals were evaluated at room temperature, -65°F and +250°F; the Phase II seals were evaluated at room temperature, -65, -100, +250, and +500°F. With the exception of the rotating shaft seal concept, all room temperature tests were conducted with differential pressures across the seal of both 15 and 30 psi. At low and high temperatures only a 15 psi differential was employed. Static leakages were determined for all of the seals and in addition dynamic leakages were determined for the reciprocating shaft seal and for the rotating shaft seal.

A. High Vacuum Environmental Equipment

The ARF high vacuum environmental equipment used for the evaluation of the seals on this program is shown in Fig. 21. The equipment consists of the following major components: (1) A 100 cfm fore pressure pump, (2) a 1.25 cfm holding pump, (3) an oil diffusion pump, (4) two refrigeration units, (5) an instrument panel and associated instrumentation, and (6) the test chamber. The 100 cfm mechanical pump (forepump) is used for initial pumping down of the test chamber to a pressure of about 10 microns. At this pressure, the diffusion pump, which has been evacuated by the holding pump to a pressure below 200 microns, is valved into the system and the mechanical pump is valved over so that it backs the oil diffusion pump. The mechanical pump can be used separately when test conditions require pressures above 10 microns. The pumping system is capable of producing ultimate pressures in the chamber as low as 2×10^{-7} mm Hg.

A three stage refrigeration unit provides a temperature of -200°F to the cold trap of the diffusion pump, while a two stage brine unit is used to obtain temperatures down to -100°F in the test chamber.

Pressures are monitored in the following manner: (1) thermocouple gages are used to obtain approximate pressure measurements at pressures down to 1 micron. (2) an alphatron gage indicates pressure quite accurately down to 1 micron. (3) an ionization gage is used for lower pressure indication down to 1×10^{-7} mm Hg. For achievement of the low temperature of -100°F as required on this program a cooling coil was mounted in the piece shown between the base plate and the test chamber in Fig. 21. The cooling coil extended up into the test chamber and was brought into intimate contact with the seal assembly under test or, in the case of the hatch seal, in contact with the hatch cover. For achievement of the high temperatures, up to +500°F, the cooling coil was replaced by a bank of 8 1000 watt T-3 quartz lamp heaters. Power for the heaters was provided through a Variac to control temperature.

The test chamber was specially designed and fabricated for this program. A section drawing showing details of the special chamber is given in Fig. 22. The chamber consisted of two volumes separated by a relatively thick plate. The larger (lower) volume was the one in which the vacuum condition was obtained while the smaller (upper) volume was the one in which atmospheric pressure or greater was

Figure 21. ARF High Vacuum Environment Facility with Special Chamber

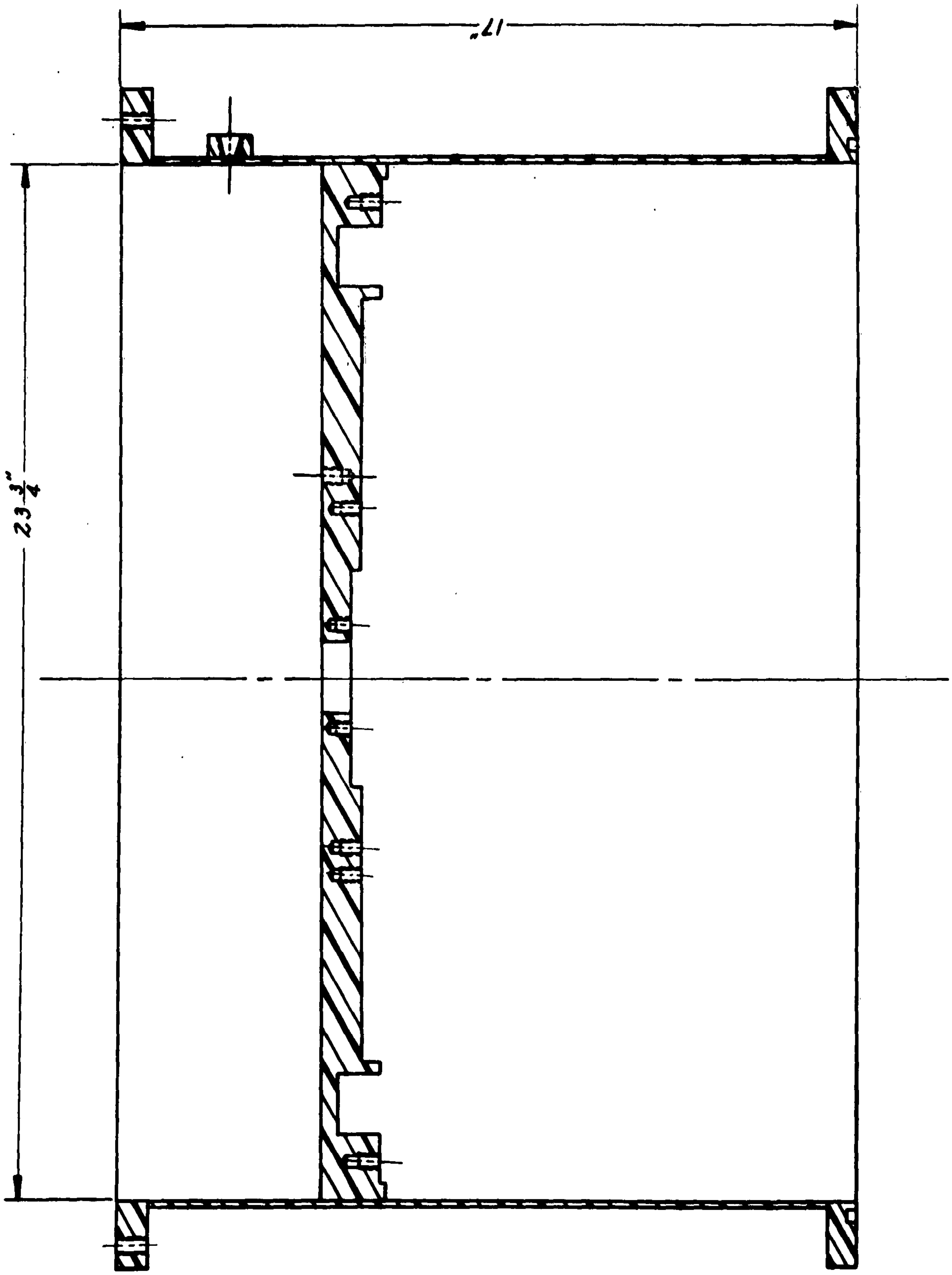

Figure 22 Cross Section of Special Pressure-Vacuum Chamber

maintained. The plate separating the two volumes had a central hole into which either the electrical seal, reciprocating shaft seal or rotating shaft seal (as shown in Fig. 23) could be mounted and attached by bolts through suitable blind tapped holes drilled into the plate. Similarly a retainer channel (shown in section in Fig. 22) was provided on the vacuum side of the plate for mounting of the hatch seal and, with the addition of a cover plate bolted in place, constituted the hatch seal concept. All of the seals with the exception of the rotating shaft seal were installed from the vacuum side of the chamber; the rotating shaft seal was installed from the pressure side of the chamber. Both ends of the chamber were open to permit access to the interior. The lower end fitted tightly against the spool piece or base plate, while the upper end was closed off by means of a tight fitting cover plate. Suitable large O-ring seals were used at either end. For testing at room temperature, the spool piece was not employed. This measure was taken to eliminate any nonessential surface area from the vacuum chamber in order to produce as high a degree of vacuum as possible. Without the spool piece the test chamber was mounted directly on the base plate.

A calibration was made of the vacuum chamber and of the pumping equipment in order to enable quantitative determination of leakages to be made during the evaluation tests. Pumping speed under operating conditions, and pressure change under pump off conditions were observed with the vacuum chamber under room temperature and under both high and low temperature conditions with a blank off plate installed in place of a test seal. The blank off plate was sealed with a metal O-ring. This procedure permits correction for system leakage, if any, from computations of seal leakage. Calibrations were repeated at times during the testing program in order to keep them up to date in the event that changes in system operation occurred.

B. Test Procedures

Each of the seal concepts was installed in turn in the test chamber. Photographs of some of the installations are given in Figs. 24 through 27. The reciprocating shaft seal is shown installed in Fig. 24. The hatch seal is shown installed in Fig. 25; note that there is a hole in the plate separating the two volumes of the test chamber. The cover plate of the hatch seal is shown installed in Fig. 26. The electrical conductor seal is shown installed in Fig. 27. With the test chamber secured, the vacuum pumps were started and, generally, the pressure in the vacuum chamber was below one micron within half an hour. Pumping was continued until the pressure appeared to stabilize. The maximum vacuum attained for each seal was dependent upon the leakage past the seal. After a stabilized condition was obtained, the maximum vacuum was noted, and a through put was calculated for a pumping speed associated with that vacuum condition. The pumping system was then valved off from the chamber. The pressure increase with time in the chamber after valving off the pumping system was obtained.

Presumably, since the only difference in each of the tests was the changing of the seals at a specific temperature, any variation from the pressure-time curve of the chamber with the reference seal (blank off plate with metal O-ring) would be due to the seal under test. Thus when the data obtained with the installed test seals was compared with that of the reference seal, the differences represented the leakage of the seal under test. As stated before, calibrations were performed at the conclusion of each series of tests to assure against changes in behavior of the vacuum

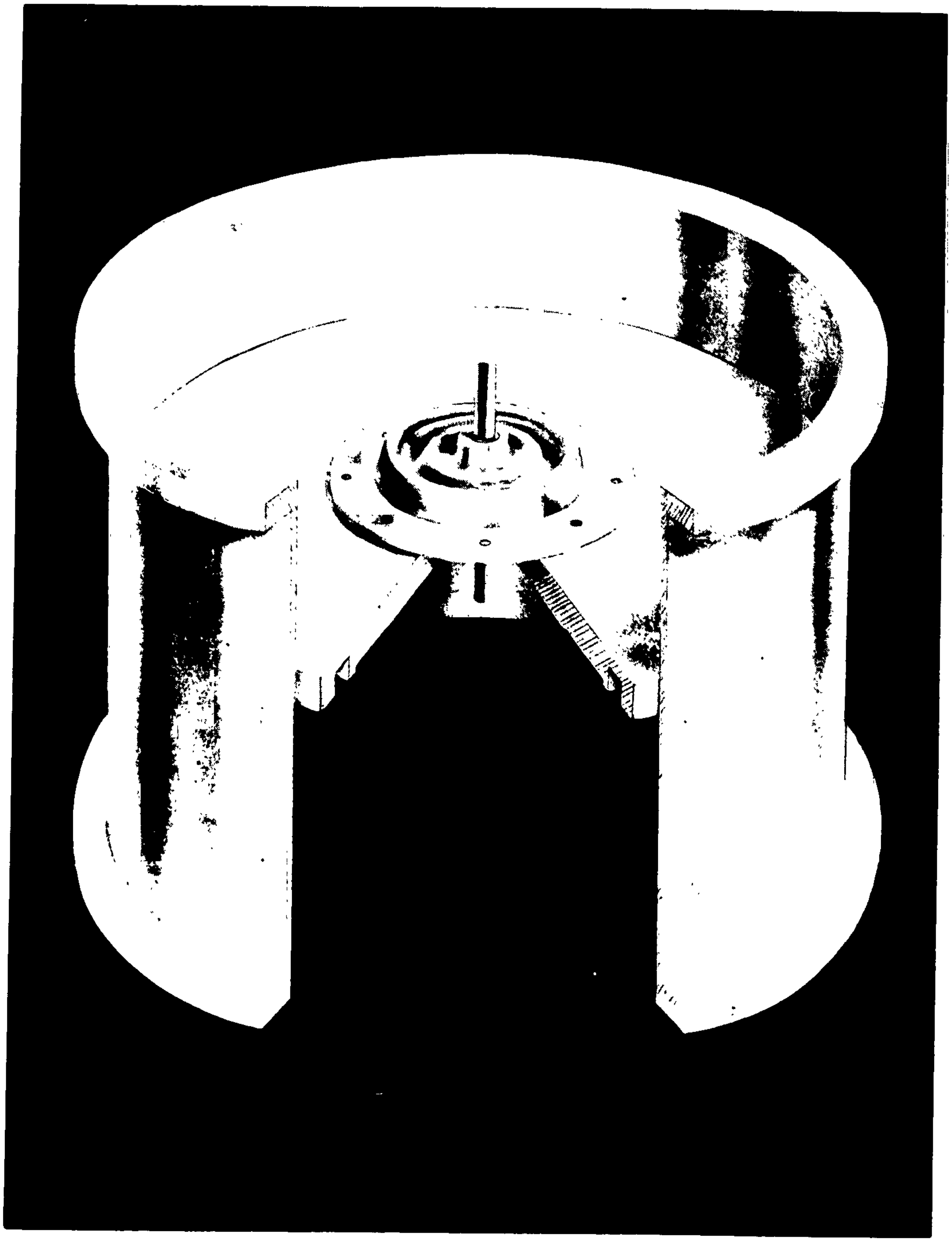

Figure 23. Details of Special Test Chamber Showing Rotating Shaft Seal Installed

Figure 24. View of Installed Reciprocating Shaft Seal

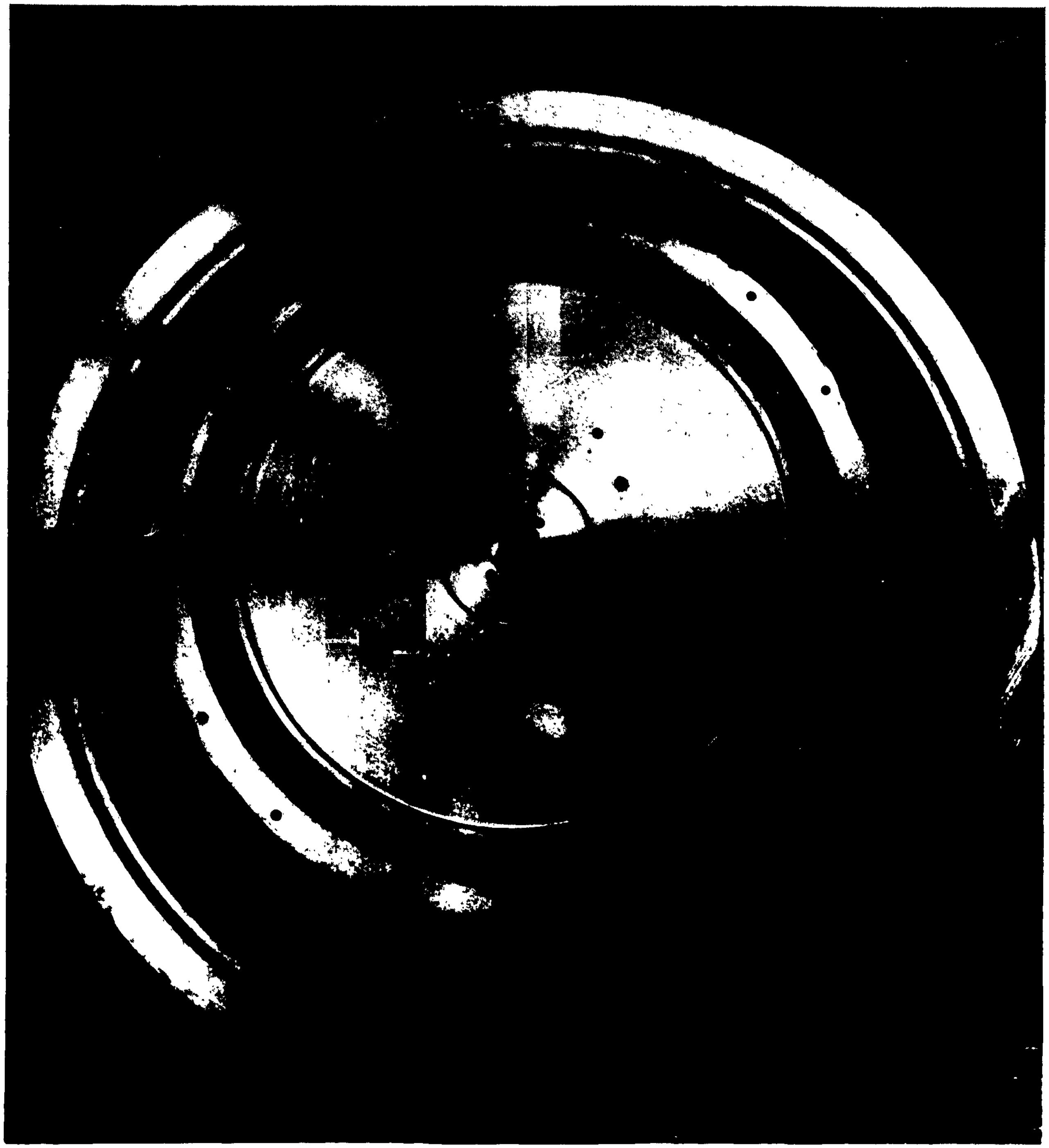

Figure 25. View of Installed Hatch Seal

Figure 26. View of Installed Hatch Cover Plate

Figure 27. View of Installed Electrical Conductor Seal

system. Some of the typical occurrences which necessitated the recalibration were distortions of the large chamber O-rings under constant reuse, and a pinhole leak which developed in the refrigerant lines cooling the chamber.

Background leakages, i.e., system leakage determined during calibrations with the reference seal, were as follows:

Chamber Temperature	Background Leakage (cc/hr)
-100°F	6.7 to 30.6
- 65°F	6.7 to 35.2
Room	1.3 to 13.3
+250°F	8.6 to 80
+500°F	11.3 to 120

Day to day variations of background leakages appeared to be random. Leakage determination is a function of pumping speed and of pressure measurement. Therefore, the accuracy of leakage determinations is a combination of accuracies of pumping speed and pressure determined from the vacuum gage. The pumping speed is believed to be accurate to ± 10 percent; while the vacuum gage is estimated to be accurate to ± 20 percent. Therefore, the leakage determinations obtained in this study are estimated to be accurate to ± 30 percent.

Movement of the shaft in the reciprocating shaft seal concept was obtained through the use of an air cylinder. The shaft was reciprocated by manual actuation of the air cylinder. Movement of the rotating shaft was accomplished with a dc variable speed motor operating at about 500 rpm. The motor is shown in position atop the chamber in Fig. 28. During tests of the reciprocating shaft seal, it was noted that pressure fluctuations would occur when the shaft was reciprocated. Therefore separate determinations of leakage were made for the shaft in the up and in the down position and in the upstroke and downstroke positions.

Temperatures (with the exception of room temperature) were determined by means of thermocouples appropriately located on the vacuum side of each seal assembly as installed for test purposes.

C. Test Results and Discussion

Results of the seal evaluation tests are summarized for each of the seal concepts in Tables 7 through 11. In each table the maximum vacuum condition attained at the specific temperature, together with the corresponding leakages for those vacuums are included.

Figure 28. ARF High Vacuum Equipment Showing Motor Drive for Rotating Shaft and Variac for Heat Regulation

The basic equation (from Ref. 13) with which leakages were calculated is

$$Q = SP$$

where

$$Q = \text{throughput in } \frac{\text{micron-liters}}{\text{sec}}$$

$$S = \text{pumping speed} = 1400 \frac{\text{liters}}{\text{sec}}$$

$$P = \text{pressure in microns Hg.}$$

Throughput can be defined as that volume of gas pumped per unit time at a given pressure. Therefore, the units above mean liters of gas pumped per second at a pressure of one micron. With proper conversion factors the units of Q can be changed to atmospheric cc/hr.

The volumetric pumping speed S can be considered constant regardless of how low the inlet pressure becomes. Therefore if we let Q_1 and P_1 be equal to the throughput and pressure respectively of a reference system and Q_2 and P_2 are defined as throughput and pressure of the seal under test then:

$$\text{Throughput through the seal} = Q_2 - Q_1 = S(P_2 - P_1)$$

The throughput so measured is considered the leakage past the seal in spite of the fact that it comprises both real air leakage and outgassing. No known method is capable of separating real air leakage from outgassing. However the Q_1 outgassing should be about equal to the Q_2 outgassing if both are measured at the same temperature.

1. Tests of Electrical Conductor Seal

Results of the evaluation tests of the electrical conductor seals are given in Table 7. Two distinct seals were tested. The first employed wires with a thermal plastic insulation and product No. 10 silicone potting compound. The second employed Teflon insulated wires and product No. 11 silicone potting compound. Tests No. 1 through 4 in Table 7 summarize the results of the first seal while tests 5 through 7 summarize results of the second seal. In both the preliminary test and test No. 1 unusually high vacuum conditions were established and the leakage rates were found to be quite small. In test No. 2 the seal behaved normally until a test temperature below -92°F was attained. As the temperature continued decreasing from -92°F the pressure in the vacuum chamber began increasing indicating that a leak was developing in the seal. It was theorized that, since the product No. 10 material is only claimed to be useful at temperatures down to -80°F by the manufacturer, a combination of shrinkage and stiffening of the potting compound may have been responsible for the increased leakage. A repeat of test No. 2 was made with another seal assembly and although the temperature reached was only -90°F behavior was not quite as good as that in test No. 2. Test No. 4 at high temperature was not unusual until a temperature believed to be 500°F was reached. After a period at the test temperature the seal appeared to behave erraticly, i.e., the pressure in the vacuum chamber as indicated by the ionization gage would increase suddenly and then decrease without apparent reason. When the test was concluded

Table 7

SUMMARY OF ELECTRICAL CONDUCTOR SEAL EVALUATION TESTS

Test No.	Seal Material	Wire Insulation	Temperature (°F)	Pressure (atmos.)	Maximum Vacuum (mm Hg)	Leakage Std. air (cc/hr)	Remarks
Prelim.	Silicone Prod. 10	Thermoplastic	Room	1	6.0×10^{-7}	2.7	
1	Silicone Prod. 10	Thermoplastic	Room	1	3.5×10^{-7}	1.1	
2	Silicone Prod. 10	Thermoplastic	-92	1	4.8×10^{-6}	1.3	Seal eventually failed at lower temperature.
3	Silicone Prod. 10	Thermoplastic	-33	1	7.8×10^{-6}	30	Repeat of test No. 2 with another seal assembly.
	Silicone Prod. 10	Thermoplastic	-90	1	8.2×10^{-6}	45	
4	Silicone Prod. 10	Thermoplastic	+280	1	2.4×10^{-6}	7.4	
	Silicone Prod. 10	Thermoplastic	+590	1	5×10^{-5}	210	Thermoplastic insulation destroyed and RTV silicone aggravated.
5	Silicone Prod. 11	Teflon	Room	1	1×10^{-6}	1.0	
	Silicone Prod. 11	Teflon	Room	2	1.05×10^{-6}	1.5	
6	Silicone Prod. 11	Teflon	-100	1	1.5×10^{-6}	3.4	
	Silicone Prod. 11	Teflon	-72	1	9.0×10^{-7}	0.07	
	Silicone Prod. 11	Teflon	-64	2	9.5×10^{-7}	0.34	
7	Silicone Prod. 11	Teflon	250	1	1.7×10^{-5}	33	
	Silicone Prod. 11	Teflon	500	1	1.8×10^{-5}	6.7	

Note:

To convert	Multiply by
cc/hr to ft^3/hr	3.5×10^{-5}
ft^3/hr to lb/yr	6.6×10^{2}
cc/hr to lb/yr	2.3×10^{-2}

and the seal was removed from the test chamber it was found that the thermal plastic insulation of the wires on the vacuum side had been charred by the heat. The silicone potting compound also appeared to have been degraded by the heat. It was later learned that the actual temperature reached by the seal was 590°F rather than 500°F. In spite of this, the results indicate that an adequate seal was maintained even at the excessive temperature.

To prevent an occurrence of the seal failure described above, the second seal type was fabricated and tested. The Teflon insulated wires and the product No. 11 silicone compound were chosen because of their better resistance to extreme temperatures. Results of tests of this seal were extremely good as shown in Table 7. At room temperature the vacuum attained was on the verge of the 10^{-7} mm Hg range but because of time limitations this vacuum was never attained. It was attained, however, at low temperatures and in fact at a temperature in the vicinity of -65° the precise leakage rate was not determinable because of the fact that the data obtained for the test seal was almost identical with that obtained for the reference seal. The resolution of the vacuum gage in the 10^{-7} mm Hg range is 1×10^{-8} mm Hg. Based on this sensitivity, the leakage for this seal was less than 0.07 cc/hr. The effect of twice atmospheric pressure above the seal at both room temperature and a temperature of -65° was hardly noticeable in comparison with tests at 1 atmosphere of pressure above the seal. The seal also behaved excellently in the elevated temperature tests.

2. Tests of Hatch Seals

Results of the hatch seal evaluation tests are summarized in Table 8. Based on a mean diameter of 18-5/8 in. for the hatch seal leakages ranged from 0.10 cc/hr/in. for the butyl seal to 1.7 for the Hypalon seal each with 9 hatch cover attaching bolts at room temperature and under 1 atmosphere of pressure differential. At low temperatures the Hypalon seal was a total failure while the silicone seal experienced leakages of 0.41 cc/hr/in. at -65° and 0.77 at -90°F. At high temperature the Hypalon seal was not very effective either, experiencing a leakage of 3.2 cc/hr/in. at a temperature of 290°F while the silicone seal at a slightly higher temperature of 305°F and at the extremely high temperature of 590°F experienced leakage of less than 0.11 cc/hr/in. At these two temperatures, the silicone seal test results were comparable to those of the reference seal and thus a precise leakage rate could not be determined. However, based upon the resolution of the vacuum gage (6.6×10^{-3} cc/hr), it may be stated that the leakage rate of the silicone hatch seal at this temperature was less than 0.11 cc/hr/in. of seal.

The failure of the Hypalon seal at low temperature may be explained by the fact that a Hypalon formulation which was not plasticized for low temperature flexibility was inadvertently employed in the fabrication by the supplier. This fact was not uncovered until after the seal had been tested and reasons for its poor behavior were investigated. It was learned that the formulation actually used had a limit of low temperature flexibility of about 0°F with a brittle point of about -42°F.

A study was made of the effect of number of attaching bolts, pressure, and permeability of the seal materials upon behavior of the various hatch seals at room temperature. The results of this study are summarized in Table 9. The results generally indicate that increased clamping force brought about by the use of 18 bolts

Table 8

SUMMARY OF HATCH SEAL EVALUATION TESTS

Test No.	Seal Material	Hatch Cover Attachment (No. of bolts)	Temperature (°F)	Pressure (atmos.)	Maximum Vacuum (mm Hg)	Leakage Std Air (cc/hr)	Leakage Rate/in. seal (cc/hr/in.)	Remarks
1	Hypalon	18	Room	1	4.1×10^{-6}	19	0.32	
	Hypalon	18	Room	2	2.8×10^{-4}	1850	31	Unaccountable
2	Hypalon	9	Room	1	1.6×10^{-5}	98	1.7	
	Hypalon	9	Room	2	5.0×10^{-5}	320	5.5	
3	Butyl	9	Room	1	1.7×10^{-5}	100	1.7	
	Butyl	9	Room	2	8.1×10^{-5}	530	9.0	
4	Silicone	9	Room	1	2.8×10^{-6}	11	0.19	
	Silicone	9	Room	2	4.2×10^{-5}	270	4.6	
5	Hypalon	9	-27	1	5.2×10^{-6}	13	0.22	Seal failed at lower temperature.
6	Silicone	9	-65	1	6.9×10^{-6}	24	0.41	
	Silicone	9	-90	1	8.2×10^{-6}	45	0.77	
7	Hypalon	9	290	1	4.2×10^{-6}	52	0.89	
8	Silicone	9	305	1	1.0×10^{-5}	<6.6	<0.11	
	Silicone	9	590	1	1.8×10^{-5}	<6.6	<0.11	
9	Butyl	18	Room	1	5.1×10^{-6}	28	0.48	
10	Butyl	18	Room	1	2.5×10^{-6}	11	0.19	
	Butyl	18	Room	2	6.9×10^{-6}	40	0.68	
11	Butyl	9	Room	1	1.8×10^{-6}	6	0.10	
	Butyl	9	Room	2	1.2×10^{-5}	74	1.3	
12	Hypalon	16	Low	1	-	-		Seal stiffened and could not function.
13	Butyl	16	-25	1	2.7×10^{-6}	12	0.20	

instead of 9 effectively improved the capability of the seals. Because the design was such to provide an outward opening hatch cover instead of an inward opening cover, the effect of increased pressure was to lessen the effectiveness of the seals and therefore increase the leakage rate. The effect of material permeability was not pronounced enough to be determined in these tests. It is theorized that the short period of time devoted to each test (approximately 1 hour at the maximum vacuum condition) was insufficient for the permeability effects to be detected.

Table 9

EFFECT OF NUMBER OF ATTACHING BOLTS AND PRESSURE UPON PERFORMANCE OF HATCH SEALS AT ROOM TEMPERATURE

Seal Material	No. of Attachment bolts	Pressure (atmos.)	Maximum Vacuum (mm Hg)	Leakage (cc/hr)
Hypalon	9	1	1.6×10^{-5}	98
Butyl	9	1	1.7×10^{-5}	100
Butyl	9	1	1.8×10^{-6}	6
Silicone	9	1	2.8×10^{-6}	11
Hypalon	9	2	5.0×10^{-5}	320
Butyl	9	2	8.1×10^{-5}	540
Butyl	9	2	1.2×10^{-5}	74
Silicone	9	2	4.2×10^{-5}	270
Hypalon	18	1	4.1×10^{-6}	19
Butyl	18	1	5.1×10^{-6}	28
Butyl	18	1	2.5×10^{-6}	11
Hypalon	18	2	2.8×10^{-4}	1850
Butyl	18	2	6.9×10^{-6}	40

3. Tests of the Reciprocating Shaft Seals

Results of the reciprocating shaft seal tests are summarized in Table 10. Generally all of the seals behaved quite well at low and high temperatures as well as at room temperature. For the seal assembly employing the buna-N O-ring sealing elements, at room temperature, the leakage with both 1 and 2 atmospheres of differential pressure was less than the resolution of the vacuum gage or less than 0.7 cc/hr with the shaft in the static position. With the shaft reciprocating, the leakages were 11 and 25 cc/hr, respectively, for 1 and 2 atmospheres. At the low temperature of -65° the leakages were 5 cc/hr and 45 cc/hr respectively, for the static and reciprocating positions. At the high temperature of 270° the leakages were 100 cc/hr and 200 cc/hr respectively for the static and reciprocating positions. All tests of the buna-N O-ring sealing elements with the exception of test No. 1 employed a silicone oil as a lubricant because petroleum base oils are not effective at extreme temperatures.

Room temperature tests of the seal assembly employing silicone O-rings revealed little difference in the performance with 1 and 2 atmospheres in the static condition but with the shaft reciprocating the leakage rate was about three times as high with 2 atmospheres as it was with 1 atmosphere of pressure differential (25 vs 8.7 cc/hr). A silicone oil was used as a lubricant at room temperature in spite of the fact that silicone rubber generally is affected adversely by silicone fluids. For tests at low and high temperatures the silicone oil was removed from the reservoir and a solid bronze bushing replaced the porous oilite type bushing. For lubrication a commercial molybdenum disulfide dry film applied to the shaft was employed.

Test results at low temperatures appeared to be erratic because readings at the low temperature of -92°F were made before readings at the more moderate temperature of -66°F. This was brought about by the fact that the temperature dropped quite rapidly when the cooling fluid was circulated. When the thermocouple indicated that the temperature was in the vicinity of -65° the vacuum in the chamber had not stabilized and was still increasing. By the time the vacuum had stabilized the temperature was far below -65° as indicated by the thermocouple. Therefore the first readings were made at -92°. Circulation of the cooling fluid was then cut off permitting the temperature in the chamber to rise. However, in so doing there may have been some expansion taking place within the chamber coupled with erratic mechanical behavior so that when the temperature again reached the vicinity of -65° the pressure inside the chamber had increased. Notable leakage differences were obtained for the shaft undergoing a downstroke and an upstroke as well as with the shaft in a down static and an up static position as noted in test 6 of Table 10. Several conditions, such as removal of particles of the dry film lubricant, slight shrinkage of the shaft O-rings, and slight diameter variations along the length of the shaft, may have combined to be responsible for this behavior.

At elevated temperatures behavior of the seals was not quite as erratic as it was at low temperatures. In test 8 time did not permit obtaining data for both the intermediate and the high temperature. Therefore, when test 9 was conducted a repeat was made of the intermediate temperature condition and data at the high temperature condition were also obtained. The temperatures actually attained were higher than had been anticipated because a calibration of the thermocouples after the tests had been completed indicated that the thermocouples were not reading properly. The calibration was prompted by the fact that upon removal of the silicone O-rings at

Table 10

SUMMARY OF RECIPROCATING SHAFT SEAL EVALUATION TESTS

Test No.	Seal Material (O-rings)	Lubricant	Reciprocating Shaft Position	Temperature (°F)	Pressure (atmos.)	Maximum Vacuum (mm Hg)	Leakage Std. air (cc/hr)	Remarks
Prelim.	Neoprene	Petroleum oil	Static	Room	1	1.0×10^{-6}	5.4	
Prelim.	Neoprene	Petroleum oil	Downstroke	Room	1	5.5×10^{-6}	30	
1	Buna N	Petroleum oil	Static	-31	1	1.8×10^{-5}	88	Lubricant froze
2	Silicone	Silicone oil (1)	Up-Static	-67	1	4.2×10^{-6}	< 0.7	
3	Silicone	Silicone oil	Up-Static	Room	1	1.8×10^{-6}	4.7	
	Silicone	Silicone oil	Const. recip.	Room	1	2.5×10^{-6}	8.7	
	Silicone	Silicone oil	Up-Static	Room	2	1.6×10^{-6}	3.7	
	Silicone	Silicone oil	Const. recip.	Room	2	5.0×10^{-6}	25	
4	Buna N	Silicone oil	Up-Static	Room	1	1.2×10^{-6}	< 0.7	
	Buna N	Silicone oil	Const. recip.	Room	1	2.7×10^{-6}	11	
	Buna N	Silicone oil	Up-Static	Room	2	1.1×10^{-6}	< 0.7	
	Buna N	Silicone oil	Const. recip.	Room	2	5.0×10^{-6}	25	
5	Buna N	Silicone oil (2)	Up-Static	-23 (4)	1	5.0×10^{-6}	11	
	Buna N	Silicone oil	Up-Static	-65 (5)	1	4.0×10^{-6}	5	
	Buna N	Silicone oil	Downstroke	-65	1	1.0×10^{-5}	45	
6	Silicone	None (3)	Up-Static	-92	1	3.0×10^{-6}	10	
	Silicone	None	Downstroke	-92	1	4.2×10^{-5}	270	
	Silicone	None	Down-Static	-66	1	9.1×10^{-6}	39	
	Silicone	None	Upstroke	-66	1	2.4×10^{-4}	1580	
	Silicone	None	Up-Static	-74	1	6.7×10^{-5}	420	
	Silicone	None	Downstroke	-74	1	1.0×10^{-4}	640	
7	Buna N	Silicone oil	Up-Static	270	1	1.7×10^{-5}	100	
	Buna N	Silicone oil	Downstroke	270	1	3.2×10^{-5}	200	
8	Silicone	MoS_2 on shaft	Up-Static	320	1	6.1×10^{-5}	400	
	Silicone	MoS_2 on shaft	Downstroke	320	1	6.9×10^{-5}	450	
	Silicone	MoS_2 on shaft	Up-Static	305	1	2.0×10^{-5}	120	
	Silicone	MoS_2 on shaft	Downstroke	305	1	4.2×10^{-5}	270	
9	Silicone	MoS_2 on shaft	Up-Static	320	1	1.9×10^{-5}	120	
	Silicone	MoS_2 on shaft	Downstroke	320	1	4.6×10^{-5}	300	
	Silicone	MoS_2 on shaft	Up-Static	560	1	1.5×10^{-5}	< 7	
	Silicone	MoS_2 on shaft	Downstroke	560	1	7.6×10^{-5}	390	See Note (6)

Notes:

(1) Company A Product No. 12 (100 centistokes).
(2) Company A Product No. 12 (320 centistokes).
(3) A dry film of MoS_2 proved faulty and was removed.
(4) Shaft immovable at this temperature under normal (90 psi) line pressure.
(5) Pressure to air cylinder increased to 150 psi - seal reciprocated.
(6) O-rings closest to heat source were deteriorated by the excessive heat.

the completion of the high temperature test, it was noted that those that were closest to the heat source had been deteriorated by the excessive heat. Since manufacturers data indicated that the silicone O-rings were capable of extended usage at 500° without deterioration, it was theorized that the temperatures were actually higher than the thermocouples indicated. Had time permitted the test of the reciprocating shaft seal would have been repeated with O-ring elements made of a silicone rubber compound which has a greater resistance to high and low temperatures (Company A product No. 9) than that of the material employed in these tests.

4. Tests of the Rotating Shaft Seals

Results of the rotating shaft seal tests are summarized in Table 11. Tests of the rotating shaft seal concept were begun with the seal assembly as shown in Figs. 7 and 8. Test No. 1 at room temperature went well with no apparent abnormal behavior of the seal. Virtually no differences in leakage were determined for the static condition and for the condition in which the shaft was rotating at approximately 500 rpm. However, when the low temperature test (test No. 2) was begun, it was impossible to obtain a high vacuum (below 1 micron) even before the test temperature conditions were attained. The seal assembly, which had been installed on the pressure side of the chamber, as noted earlier in this report, was removed from the chamber. Upon inspection it was noted that a pin hole leak had developed in the silicone RTV compound bridging the elements of the diaphragm together. Apparently this leak was brought about by distortions of the diaphragm under the 15 psi differential pressure. It was noted that the diaphragm had undergone a permanent deformation. Apparently the leak occurred because of a poor bond between the silicone RTV material and the aluminum diaphragm.

A new seal assembly was fabricated using the rigid unslotted diaphragm and was fitted with the Teflon sealing elements and the silicone lubricant. The test of the new seal assembly at room temperature (test No. 3) yielded surprisingly good results by comparison with test No. 1. Leakages were less by an order of magnitude than in test No. 1 because of the use of the solid rather than the slotted diaphragms. Performance of the seal at low temperature was also good in spite of some erratic behavior as the temperature was being reduced. The minimum temperature achieved was only -60°F, because of difficulties with the cooling coils. The high temperature test could not be performed because the leakage past the seal was such that a high vacuum could not be attained. The actual Teflon sealing elements employed were designed for much larger pressure differentials than were experienced in these tests. This fact coupled with the fact that the Teflon material was quite stiff and the shaft may have been slightly undersize could have been responsible for the inability of the sealing elements to perform effectively.

For tests of the silicone sealing elements the lubricant was removed and the porous oilite bearing was replaced with a solid bronze bushing. For lubrication a dry film molybdenum disulfide coated shaft was employed. Generally performance of the silicone sealing elements was not as good as that of the Teflon elements at room temperature. However at the extreme temperatures, both high and low, performance of the silicone elements was far better than that of the Teflon elements.

Upon removal of the rotating shaft seal with the silicone elements from the test chamber after completion of the high temperature tests, it was noticed that

Table 11

SUMMARY OF ROTATING SHAFT SEAL EVALUATION TESTS

Test No.	Seal Material	Lubricant	Rotating Shaft Speed (rpm)	Temperature (°F)	Pressure (atmos.)	Maximum Vacuum (mm Hg)	Leakage Std. Air (cc/hr)	Remarks
1	Silicone	Silicone Fluid	Static	Room	1	7.9×10^{-5}	520	
	Silicone	Silicone Fluid	500	Room	1	8.1×10^{-5}	540	
2	Silicone	Silicone Fluid	-	Low	1	-	-	Diaphragm failure before test conditions were attained.
3	Teflon	Silicone Fluid	Static	Room	1	2.7×10^{-6}	12	New rigid diaphragms (unslitted).
	Teflon	Silicone Fluid	500	Room	1	2.9×10^{-6}	14	
4	Teflon	Silicone Fluid	500	-27	1	2.4×10^{-5}	150	
	Teflon	Silicone Fluid	Static	-27	1	2.4×10^{-5}	150	
5	Teflon	Silicone Fluid	500	-47	1	1.6×10^{-5}	100	Pressure in vacuum chamber increased to 120 μ shortly after but test continued.
	Teflon	Silicone Fluid	500	-60	1	7.5×10^{-4}	5000	Pressure increased to 46 μ.
6	Teflon	Silicone Fluid		High	1			Leakage so bad that high vacuum could not be attained.
7	Silicone	MoS_2 coated shaft	Static	Room	1	3.9×10^{-5}	250	
	Silicone	MoS_2 coated shaft	500	Room	1	3.7×10^{-5}	240	
8	Silicone	MoS_2 coated shaft	500	-65	1	1.8×10^{-4}	1200	
	Silicone	MoS_2 coated shaft	Static	-77	1	2.6×10^{-4}	1700	
	Silicone	MoS_2 coated shaft	500	-77	1	2.4×10^{-4}	1600	
9	Silicone	MoS_2 coated shaft	500	300	1	3.8×10^{-5}	240	
	Silicone	MoS_2 coated shaft	Static	305	1	3.9×10^{-5}	250	
	Silicone	MoS_2 coated shaft	500	495	1	5.4×10^{-5}	250	
	Silicone	MoS_2 coated shaft	Static	520	1	5.3×10^{-5}	240	

considerable wear had been experienced by both the shaft and the sealing elements. At the end of the shaft which projected into the vacuum chamber in the heated zone, it was also noted that the molybdenum disulfide coating had almost completely flaked off. Either the shaft had experienced temperatures in excess of the 600°F specified by Company C as the upper temperature for which their product No. 4 was designed to lubricate, or the coating broke down under the combined high temperature and high vacuum condition.

D. Effect of Permeability upon Total Leakage for the Hatch Seals

A study was made of the effect of air permeability upon the measured total leakage for the hatch seals at room and elevated temperatures. Using permeability data obtained from reference 3, calculations were made of air permeation through the hatch seal by assuming that the outer unsupported wall of the hatch seal was subjected to a differential pressure of 1 atmosphere through its thickness of 0.156 in. The width of the unsupported area was assumed to be 1.25 in. and the length or perimeter of the hatch seal was determined to be 64.1 in. The following formula was used in the calculation of the quantity of air permeating the seal:

$$q = \frac{Q\,A\,\Delta P\,t}{d}$$

where

q = quantity of gas

Q = permeability coefficient

t = time

A = area of the member under pressure difference

d = thickness

ΔP = pressure differential.

Results of the calculation are given in Table 12 wherein the theoretical air loss through permeation is compared with the measured total leakage for the hatch seals. It is noted that the air loss through permeation for the butyl and the Hypalon seal is only a small fraction of the total leakage, whereas for the silicone seal permeation is comparable with total leakage at room temperature and is considerably greater at elevated temperatures. This behavior for the butyl and the Hypalon seals was expected. However, the behavior of the silicone seals was peculiar. By way of explanation it is theorized that the effective width of the unsupported wall of the hatch seal was considerably less than the assumed 1.25 in. Also the actual seal temperature may have been considerably less than the reported environment temperature when the tests of the silicone seal were performed. Likewise the time undoubtedly was too brief for the air permeability to stabilize. These three factors combined could have resulted in a smaller air loss through permeation than was calculated. At any rate it can be generally stated that for materials with a low permeability coefficient, air loss through permeation will be a small factor in comparison with leakage produced by other causes. Whereas for materials such as silicone, with high permeability coefficients, air loss through permeation will be a large factor in comparison with leakage from other causes.

Table 12

THEORETICAL AIR LOSS THROUGH PERMEATION FOR HATCH SEAL COMPARED WITH MEASURED TOTAL LEAKAGE

Material	Temperature (°F)	Permeability Coefficient (10^{-7}cc/sec/cm^2/cm)	Permeation through seal (cc/hr)	Permeation in one year (lb/yr)	Total Leakage (lb/yr)
Butyl	Room (75)	0.02	0.0012	0.00028	0.14 - 2.3
Hypalon	Room	0.72	0.33	0.0077	0.44 - 2.3
Hypalon	250	2.3	1.07	0.025	1.2
Hypalon	350	6.2	2.9	0.067	-
Silicone	Room	11 - 35	5.1 - 15.3	0.12 - 0.35	0.25
Silicone	250	50 - 70	23.2 - 30.6	0.54 - 0.71	<0.15
Silicone	350	69 - 113	30.2 - 51.3	0.70 - 1.2	-
Silicone	500	75 - 130	32.8 - 60.2	0.76 - 1.4	<0.15

IX. SUMMARY AND CONCLUSIONS

A complete summary of performance of the four seal types each tested with two different materials, is presented in Table 13. From the data obtained in tests of short duration (approximately 1 hr at the test temperature) the leakage rates have been projected for a one year period and are given in the table in units of pounds of standard air per year. Because the data have been determined from relatively short time tests, and because material changes can occur with time at temperature, (as noted in Ref. 14) extreme caution should be used in the application of the data to actual designs until, and only at a time when, such data are available from long term tests.

Based on the results of short time tests reported here, the following conclusions may be drawn in regard to the four seal concepts: The electrical conductor seal concept employing the Company F product No. 10 silicone compound demonstrated satisfactory performance capabilities for the Phase I application. The electrical conductor seal employing the Company A product No. 11 silicone compound performed generally better than the product No. 10 seal and is considered satisfactory for both the Phase I and the Phase II applications. The concept developed here is applicable strictly to loose bundles of lead-through or instrumentation wires. The concept is applicable with caution to unshielded cables; however, further work is necessary for the development of a satisfactory technique for sealing shielded cables.

Results of the evaluation of the hatch seal concept indicate that even though the Hypalon material failed at low temperatures, performance otherwise for the Phase I application was satisfactory. There is every reason to believe that a properly plasticized Hypalon formulation would offer satisfactory performance at low temperatures as well as at the upper temperature of the Phase I application. Selection of the Company A product No. 9 silicone material for the hatch seal proved to be an excellent one. The silicone hatch seal performed satisfactorily for both the Phase I and the Phase II applications. Although no attempt was made to evaluate the seal under repeated open-close conditions, it is believed that the design is capable of long life under such conditions. The design is also believed to be capable of a high degree of sealing in spite of any minor dimensional irregularities in a frame or in a hatch cover.

For the reciprocating shaft seal concept, the Buna-N O-ring sealing elements demonstrated good performance for the Phase I sealing application. The silicone O-ring sealing elements showed not quite as good a performance for the Phase I sealing application as the Buna-N elements. However, performance overall and especially for the Phase II application is considered to be satisfactory. Because this is a dynamic sealing application, performance was somewhat less than either of the two static sealing applications (the electrical conductor seal and the hatch seal). The unique feature of the reciprocating shaft seal concept, permitting misalignments and transverse displacements to be incurred by the shaft without impairing sealing effectiveness, is strongly recommended as an integral part of any reciprocating shaft seal concept. It must be understood that the reciprocating shaft seal is a dynamic sealing application, hence, it is necessary to accept a somewhat lower level of performance than for the static sealing applications characterized by the electrical conductor seal and the hatch seal.

Table 13

PROJECTED LEAKAGE RATES (FOR ONE YEAR) FOR SEALS UNDER HIGH VACUUM WITH ONE ATMOSPHERE OF PRESSURE DIFFERENTIAL AT VARIOUS TEMPERATURES

Temper-ature (°F)	Condition	Seal Type and Material: Electrical Conductor Seal		Hatch Seal (9 bolts)		Reciprocating Shaft Seal		Rotating Shaft Seal	
		Prod. 10	Prod. 11	Hypalon	Silicone	Buna N	Silicone	Teflon	Silicone
		(lb yr)		(lb/yr/in.)		(lb/yr)		(lb/yr)	
-100	Static	failed	0.079	-	0.018	-	0.23	-	39
	Dynamic	-	-	-	-	-	6.3	-	37
-65	Static	0.70-1.05	<0.0016	failed	0.0095	0.11	0.93-10	-	28
	Dynamic	-	-	-	-	1.1	15-36	116	28
Room	Static	0.025	0.023	0.0074-0.039	0.0044	<0.00015	0.11	0.28	5.8-12
	Dynamic	-	-	-	-	0.25	0.20	0.32	5.6-13
+250	Static	0.17	0.77	0.020	<0.0026	2.3	2.8-9.3	failed	5.8
	Dynamic	-	-	-	-	4.6	6.3-11	-	5.6
+500	Static	4.9	0.16	-	<0.0026	-	<0.0015	-	5.6
	Dynamic	-	-	-	-	-	9.3	-	5.8

(1) 0.03 to 1.05 at -90°F.

Lubrication of a reciprocating shaft in an extreme temperature combined with high vacuum environment, is a problem which was not fully resolved on this program. A satisfactory lubricant for the Buna-N O-rings of the Phase I sealing application was the Company A product No. 12 silicone fluid with a viscosity of about 300 centistokes. Buna-N rubber has a tendency to shrink slightly when immersed or exposed to silicone fluids. Therefore, proper allowances must be made in the design of the O-ring retainers to compensate for such volume changes in order to retain effectiveness of the seal over prolonged periods of time. Silicone fluids on the other hand cannot be used as lubricants in the presence of silicone rubber seals, because of the poor resistance of silicone rubbers to the silicone fluids. The combination of a lubricant reservoir together with a porous oilite type bushing will adequately maintain lubrication in spite of the evaporation of the lubricant in the presence of a high vacuum. The dry film lubricant coating on the shaft investigated on this program (Company C product No. 4) proved unsatisfactory in these tests because of the tendency for the coating to be easily removed by the rubbing action of the rubber seals on the coating. If a reasonable amount of friction can be tolerated in a reciprocating shaft application it may be preferable to utilize no lubricant at all; the silicone sealing element being capable of tolerating whatever temperatures may be developed by the friction. However, it is believed that further studies are required in order to develop a more satisfactory lubrication system for the Phase II application.

The rotating shaft seal concept employing the Teflon lip type sealing elements did not demonstrate satisfactory performance for the Phase I sealing application in spite of the fact that the Teflon material is specified by the manufacturer as being capable of withstanding the broad temperature extremes of Phase II as well as those of Phase I. The apparent cause of the poor performance of the Teflon elements is that the elements were likely designed for much higher differential pressures. Consequently, the small differential pressure of only 15 psi was inadequate to deflect the stiff seals much less to seal them tightly around the shaft.

The rotating shaft seal with the silicone sealing elements demonstrated a fairly satisfactory sealing capability for room temperature and elevated temperature applications, but at low temperatures its performance was not considered satisfactory. Further investigations are required in order to develop a rotating shaft seal concept which will perform adequately for long periods of time in flight vehicle cabins. The comments made regarding lubrication of the reciprocating shaft seal concept also apply to the rotating shaft seal concept. In spite of the failure of the shaft alignment technique characterized by the slitted diaphragms, the successful shaft alignment technique employed for the reciprocating shaft seal could be made applicable to the rotating shaft seal concept.

REFERENCES

1. Matacek, G. F., "Vacuum Volatility of Organic Resins", WADC TR 59-268, Sept. 1959 (also Matacek, G. F., "Vacuum Volatility of Organic Coatings", paper in Surface Effects on Spacecraft Materials, Clauss, F. J. (Ed.), John Wiley and Sons, Inc., New York, (1960).

2. Mattice, J. J., "Vacuum - Thermal Stability of Organic Coating Materials, Part I - Polyurethanes", WADD TR 60-126, Nov. 1959.

3. Hayes, R. A., Smith, F. M., Smith, W. A., and Kitchen, L. J., "Research on High Temperature Resistant Rubber Compounds", WADC TR 56-331, Part II, Feb. 1958, ASTIA AD No. 15103.

4. Ossefort, Z. T., and Ruby, J. D., "The Effects of a Simulated Space Environment on the Properties of Elastomers", 1961 Proceedings IES National Meeting, 651, Washington, Apr. 6-7, 1961.

5. Bopp, C. D. and Sisman, O., "Radiation Stability of Plastics and Elastomers", Nucleonics, July 1955.

6. Harrington, R., "Elastomers for Use in Radiation Fields, Part IV - Effects of Gamma Radiation on Miscellaneous Elastomers and Rubber-like Plastic Materials", Rubber Age, June 1958.

7. Johnston, R. S., "Mercury Life Support System", IAS S.M.F. Fund Paper No. FF-25, presented at IAS 28th Annual Meeting, New York, Jan. 25-27, 1960.

8. Fick, A., Ann. Physik. 94, 59, (1855).

9. Anon., Atom Movements, American Society for Metals, Cleveland, 1951.

10. Van Amerongen, G. J., "The Flow of Gases through High Polymer Films in Equilibrium with Sorbed Vapors", J. Applied Physics, 17, 972 (1946); Rubber Chem. and Technol., 20, 494 (1947), 24, 109 (1951); J. Polymer Sci., 5 307 (1950).

11. Whitby, G. S., Synthetic Rubber, John Wiley and Sons, Inc., New York, (1954).

12. Pilar, F. L., "The Permeability of Different Rubbers to Gases and Its Relation to Diffusivity and Solubility", J. Polymer Sci., 45, 205 (1960).

13. Farkass, I. and Barry, E. J., "Study of Sealants for Space Environment", NRC Research Project No. 43-1-139 Summary Report, June 4, 1960.

14. Anon., "Hermetic Seals", Electromechanical Des., October 1960; also "High Vacuum Sealing Techniques", Electronic Equip. Eng., March 1961.

BIBLIOGRAPHY

Jordan, J. R. and Young, R., "Molecular Sealing", unpublished paper Parker Seal Company, Culver City, Calif.

Jordan, J. R., Carrel, T. and Young, R., "Seals for Hard Vacuums", Machine Design, 134, May 25, 1961.

Clauss, F. J., Mauri, R. E., et al, "Evaluating the Behavior of Materials under Space Conditions", 1961 Proceedings IES National Meeting, Washington, 475, April 5-7, 1961.

CODE SHEET

Company	Code Letter
Dow Corning Corporation Midland, Michigan	A
Garlock, Incorporated Palmyra, New York	B
Everlube Corporation North Hollywood, California	C
Parker Rubber Division Parker-Hannifin Corporation Cleveland, Ohio	D
Acadia Synthetic Products Division Western Felt Works Chicago, Illinois	E
General Electric Company Silicone Product Division Waterford, New York	F

Product	Code Number
Silastic No. 50	1
Klozure Type 63 x 287	2
Klozure Type 62 x 287	3
Compound 620	4
Compound No. N304-7	5
Compound No. S451-7	6
Compound No. 46063GE	7
Compound No. 96E-1944	8
Silastic 675	9
RTV 11	10
Silastic RTV 601	11
510 Fluid	12
Silastic RTV 502	13
Silastic RTV Thinner	14

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ARMOUR RESEARCH FOUNDATION, Chicago, Ill. RESEARCH AND DEVELOPMENT OF DESIGN CONCEPTS FOR SEALING APPLICATIONS IN AEROSPACE VEHICLE CABINS, by J. S. Islinger, February 1962. 68 p. incl. illus. tables, 14 refs. (Project 1368; Task 13806) (ASD TR 61-696) (Contract AF 33(616)-7194)

Unclassified Report

This report describes the development of near absolute sealing techniques for small openings, such as for electrical conductors, reciprocating and rotating shafts, and hatches in the walls of flight vehicle cabins. The need for absolute sealing stems from the requirement of a habitable environment in such vehicles for periods as long as one year under differential pressure and

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temperature extremes from -100 to +500°F. The considerations underlying selection of suitable seal materials for resistance to the space environment, comprising radiation, high vacuum, temperature and static and dynamic loading, are discussed. The mechanical design and material factors considered conducive to and studies leading to a definition of absolute sealing are also discussed. Special investigations concerned with effect of elastomer permeability upon seal behavior and with techniques for adequately sealing electrical wires and cables were undertaken and are described. The developed seal concepts are described in detail and results of the evaluation tests performed under simulated environmental conditions in the ARF high vacuum environmental facility are presented.

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